

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

TRW REPORT

32937-6001-TIU-00

NASA CR 159581

(NASA-CR-159581) HEAT PIPE LIFE AND
PROCESSING STUDY Final Report (TRW Defense
and Space Systems Group) 94 p HC A05/MF A01

N79-25349

CSCL 20D

Unclass

G3/34 23404

HEAT PIPE LIFE AND PROCESSING STUDY

FINAL REPORT

prepared for

NASA LEWIS RESEARCH CENTER

CLEVELAND, OHIO 44135

CONTRACT NAS 3-21200

TRW SALES NO. 32937.000

APRIL 12, 1979



TRW

DEFENSE AND SPACE SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH • CALIFORNIA

TRW REPORT
32937-6001-TU-00

NASA CR 159581

HEAT PIPE LIFE AND PROCESSING STUDY

FINAL REPORT

prepared for

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

CONTRACT NAS 3-21200

TRW SALES NO. 32937.000

APRIL 12, 1979

TRW
DEFENSE AND SPACE SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH • CALIFORNIA

CONTENTS

	Page
1.0 INTRODUCTION	1-1
2.0 BACKGROUND AND BASIS OF CONCEPT.	2-1
3.0 PHASE I COUPON TEST.	3-1
3.1 Test Procedure.	3-1
3.2 Coupon Analysis	3-9
3.2.1 Reflectance Measurements	3-9
3.2.2 Microscope Observation	3-9
3.3 Summary and Conclusion.	3-18
4.0 PHASE II: HEAT PIPE MATRIX.	4-1
4.1 Processing Flow Chart	4-1
4.2 Heat Pipe Fabrication	4-4
4.3 Heat Pipe Processing And Fill	4-6
4.4 Calculation Of Gas Inventories.	4-6
4.5 Heat Pipe Matrix Test Results	4-13
4.5.1 Individual Test Results.	4-13
4.5.2 Group Test Results	4-36
4.5.3 Conclusion	4-48
5.0 EFFECT OF GAS ON HEAT PIPE PERFORMANCE	5-1
5.1 Simple Heat Pipe Models	5-1
5.1.1 Results.	5-4
5.2 Variable Conductance Heat Pipe Model.	5-12
5.2.1 Results.	5-12
6.0 SUMMARY AND CONCLUSION	6-1

1.0 INTRODUCTION

TRW Defense and Space Systems Group has completed a long term test and evaluation program, "Heat Pipe Life and Processing Study". This program (Contract NAS 3-21200) was concerned with the development of improved processing techniques for materials used in heat pipe fabrication. Non-condensable gas is generated as the heat pipe working fluid (ammonia in this case) reacts with the wick and wall materials and with any impurities which might be present in the assembled heat pipe. A novel approach to reducing the gas generation rate between aluminum and ammonia was evaluated in a series of coupon tests followed by long term tests of 18 heat pipes. The technique employed was the addition of various amounts of water to the ammonia charge used to reflux the heat pipe during the last processing step before adding the final charge. Heat pipes in the test matrix included two groups: nine were cleaned using a series solvents and nine were cleaned with chemical (Alkaline) cleaner.

Quantitative measurements of non-condensable gas were made by measuring the temperature profile of the test heat pipes while under load in a low-temperature chamber. Temperature profile data was computer-analyzed to compute gas quantities. A complete set of temperature profile data for all heat pipes will be presented to illustrate how the data was analyzed. Resulting gas generation data is then presented for all heat pipes in the test matrix.

A series of thermal calculations was performed for realistic heat pipe hardware in a spacecraft application. Both simple "isothermalizer" and variable conductance heat pipe configurations were analyzed. The effect of various quantities of non-condensable gas was determined and results are presented graphically.

TRW Defense and Space Systems Group has been studying the effects of heat pipe processing variables on the generation of non-condensable gas since 1964. During the many years of fabrication experience, a number of sets of processing steps and procedures has been developed at TRW and throughout the industry to minimize the generation of this unwanted gas in heat pipes. We will address the impact of gas in heat pipes in Section 6. The information to be presented amply illustrates the need to control such unwanted gas generation. Beginning in 1974, TRW began studying ammonia heat pipe processing variables for NASA LeRC. Under Contracts NAS3-19128 and NAS3-20782 the effects of cleaning technique, surface area, temperature, galvanic couple and finally water on gas generation in aluminum, stainless steel, and combination heat pipes was studied.

The most recent long-life (32 months) test on ammonia heat pipes by TRW, completed under Contract NAS3-20782⁽¹⁾, provided the basis for direction under the present contract. The key issue to be examined was the role of water in surface passivation. The results of the referenced report indicate two significant factors: 1.) short term data (< 1 year) on gas generation may not provide a basis for long term projections, and 2.) the role of water in ammonia heat pipe passivation is a complex issue. The long term results showed a resumption of gas generation by the water-added heat pipes comparable to the conventionally processed pipes. It was suggested that the presence of water over long periods of time may defeat any passivation which occurs early in life (< 1 year). Temperature-induced cracking of protective films is a possible cause for this observation. The present program focussed on the addition of water during reflux only for passivation, and the use of water-free ammonia for the final charge.

The program was originally planned to be divided into three parts: the first phase was to be a preliminary screening phase in

⁽¹⁾D. Antoniuk and E. Luedke, "Heat Pipe Materials Compatibility Extended Report", TRW Report 31132-6001-RV-00, December 1977.

which aluminum coupons were exposed to varying ammonia/water mixtures and examined optically; a second phase in which 6 heat pipes were to be studied for a short term (60 days) exposure, and the third phase in which 12 heat pipes were to be tested for seven months. After Phase 1 was completed, it was recommended that all 18 of the heat pipes be placed in a single, longer term (9 month) test matrix. This recommendation was followed and the program completed with this two-phase approach. Using this approach more long term data was generated with additional heat pipes. The results of each phase of the program will be discussed separately.

3.0 PHASE I COUPON TEST

The objective of this preliminary phase of the program was to determine the effectiveness of proposed heat pipe processing parameters in improving materials compatibility in aluminum 6051 pipe/5056 fiber wick/ammonia heat pipe systems. The proposed study was to be conducted utilizing small samples of these materials, i.e., 6061 Al test coupons made from 0.040" thick sheet stock and 5050 Al coupons machined from 3/8" dia rods. The configuration of these coupons are shown in Figure 3-1.

In the original statement of work, only 6061 Al coupons were to be included in the study. However, the metal fiber slab wick can only be fabricated from 5056 Al. In terms of surface area per unit length of pipe in the wick area is 10 times greater than the surface area of the pipe; therefore, it was decided to include the 5056 coupons in the test matrix also.

The tentative proposal coupon test matrix is shown in Table 3-1. During Phase 1 of the study this coupon matrix was expanded to that shown in Table 3-2 (March 78).

Two cleaning processes were included, chemical cleaning and solvent cleaning, whose procedures are shown in Figures 3-2 and 3-3, respectively. In addition, as seen in Table 3-2, for samples 15 and 16, pure ammonia was included as a refluxing parameter in order to offer a basis of comparison with H₂O-ammonia solutions.

3.1 Test Procedure

To simulate the high temperature reflux steps in heat pipe processing, six test pressure vessels were fabricated from all CRES 304 components as shown in Figure 3-4. As shown in Figure 3-5, the test coupon is placed inside a glass container to isolate the test samples from the walls of the pressure vessel. Also shown is a fill tube welded to the top vessel cap to place the refluxing fluid charge directly into the glass container. This prevents

ORIGINAL PAGE IS
OF POOR QUALITY

SK 78001		REVISIONS			
LTR		DESCRIPTION		DATE	APPROVED
<p>-1 COUPON DETAIL SCALE ~ 5/1</p> <p>-2 COUPON DETAIL SCALE ~ 2/1</p>					
QTY REQ'D	ITEM NO.	DESCRIPTION	MATERIAL		
ENGINEERING SKETCH		<p>TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH, CALIFORNIA</p> <p>ORIGINATOR DATE MATERIALS COMPATIBILITY 6061-T6 AL D ANTONIUK 1/27/78 AND 6056 AL TEST COUPONS</p> <p>SIZE CODE IDENT NO. SHEET 1 OF</p> <p>A 11982 SK 78001</p> <p>SCALE</p> <p>MJO</p>			

Figure 3-1. Test Coupons Configuration

Table 3-1
PROPOSAL COUPON MATRIX

Sample	Water/Ammonia Concentration*	Temperature	Material	Time (hrs.)
1	.25% H ₂ O	100°C	Aluminum	20
2	.5%	100°C	Aluminum	20
4	1.0%	100°C	Aluminum	20
8	3.0%	100°C	Aluminum	20
12	10%	100°C	Aluminum	20
7	3%	80°C	Aluminum	20
6	3%	60°C	Aluminum	20
10	3%	100°C	Aluminum/Stainless Steel	20
3	1.0%	100°C	Aluminum	5
5	1.0%	100°C	Aluminum	100
9	3%	100°C	Aluminum/Stainless Steel	5
11	3%	100°C	Aluminum/Stainless Steel	100

*Concentration by weight

Table 3-2
ACTUAL COUPON TEST MATRIX

Sample	Water/Ammonia Concentration*	Temperature	Material	Time (hrs.)
(9), (10)	.23% H ₂ O	100°C +0 -2	Aluminum 6061	20
(7), (8)	.52%	100°C +0 -2	Aluminum 6061	20
(5), (6)	.97%	100°C +0 -2	Aluminum 6061	20
(3), (4)	3.1%	100°C +0 -2	Aluminum 6061	20
(1), (2)	10.5%	100°C +0 -2	Aluminum 6061	20
(29), (30)	3.0%	80°C ±2	Aluminum 6061	20
(21), (22)	3.0%	60°C ±2	Aluminum 6061	20
(17), (18)	3.0%	100°C +0 -2	Aluminum/Stainless Steel 6061 / 304	20
(19), (20)	1.1%	100°C +0 -2	Aluminum 6061	5
(23), (24)	1.1%	100°C +0 -2	Aluminum 6061	100
(25), (26)	3.0%	100°C +0 -2	Aluminum/Stainless Steel 6061 / 304	5
(27), (28)	3.0%	100°C +0 -2	Aluminum/Stainless Steel 6061 / 304	100
(13), (14)	10.5%	100°C +0 -2	Aluminum 5056	20
(15), (16)	0%	100°C +0 -2	Aluminum 6061	20

- Chemically Cleaned

- Solvent Cleaned

*Concentration by weight

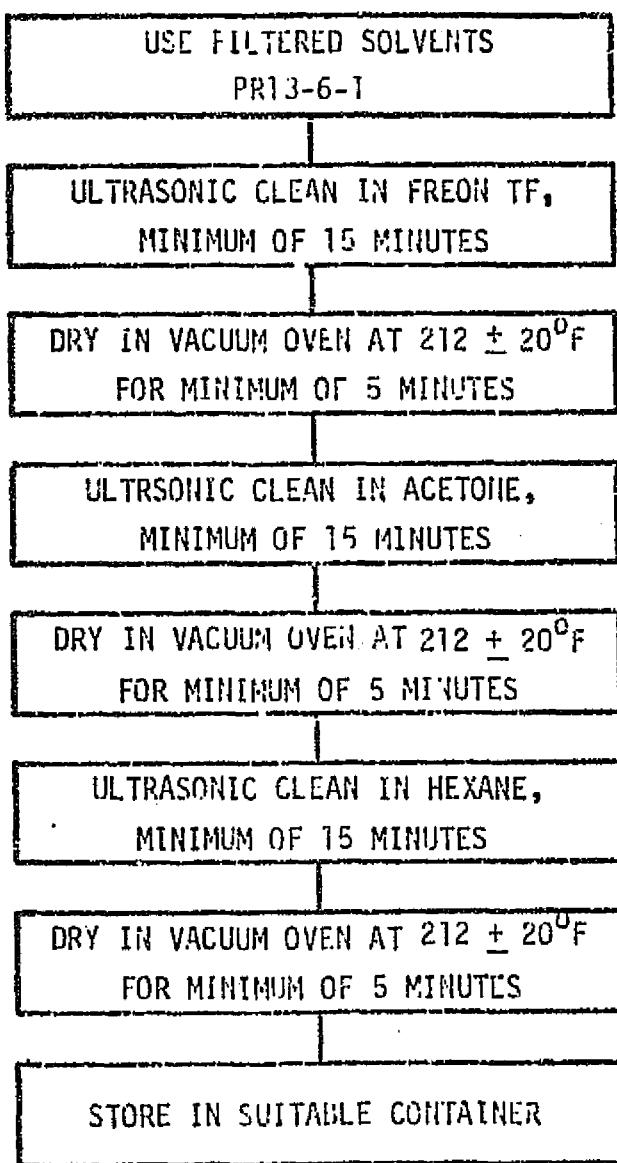


Figure 3-2. Solvent Cleaning Procedure

CRP7-10

1. Ultra-sonically clean in FREON PCA (TF) for 10 to 15 minutes. Hold in vapor phase for 3 to 5 minutes.
2. Blow dry with heated 120°F to 150°F nitrogen.
3. Ultra-sonically clean in TURCO 4215 for 10 to 15 minutes.
4. Rinse in deionized water until pH equals system water. Use ultra-sonic energy.

CAUTION: Parts must not remain wet with water for more than 4 hours. If cleaning is interrupted for any reason, complete drying cycle.

5. Immerse in chromated deoxidizer 8 to 10 minutes. Use ultra-sonic energy.
6. Rinse in deionized water per Step 4.
7. Blow off excess water with heated 120°F - 150°F GN₂.
8. Rinse in isopropyl alcohol 5 minutes. Use ultra-sonic energy.
9. Blow off excess alcohol with heated nitrogen (120°F - 150°F).
10. Vacuum dry 180°F for 2 hours. Back fill with GN₂.
11. Package each component individually per PR 2-2.

REVISED: 6-16-75

Figure 3-3. Chemical Cleaning Procedure

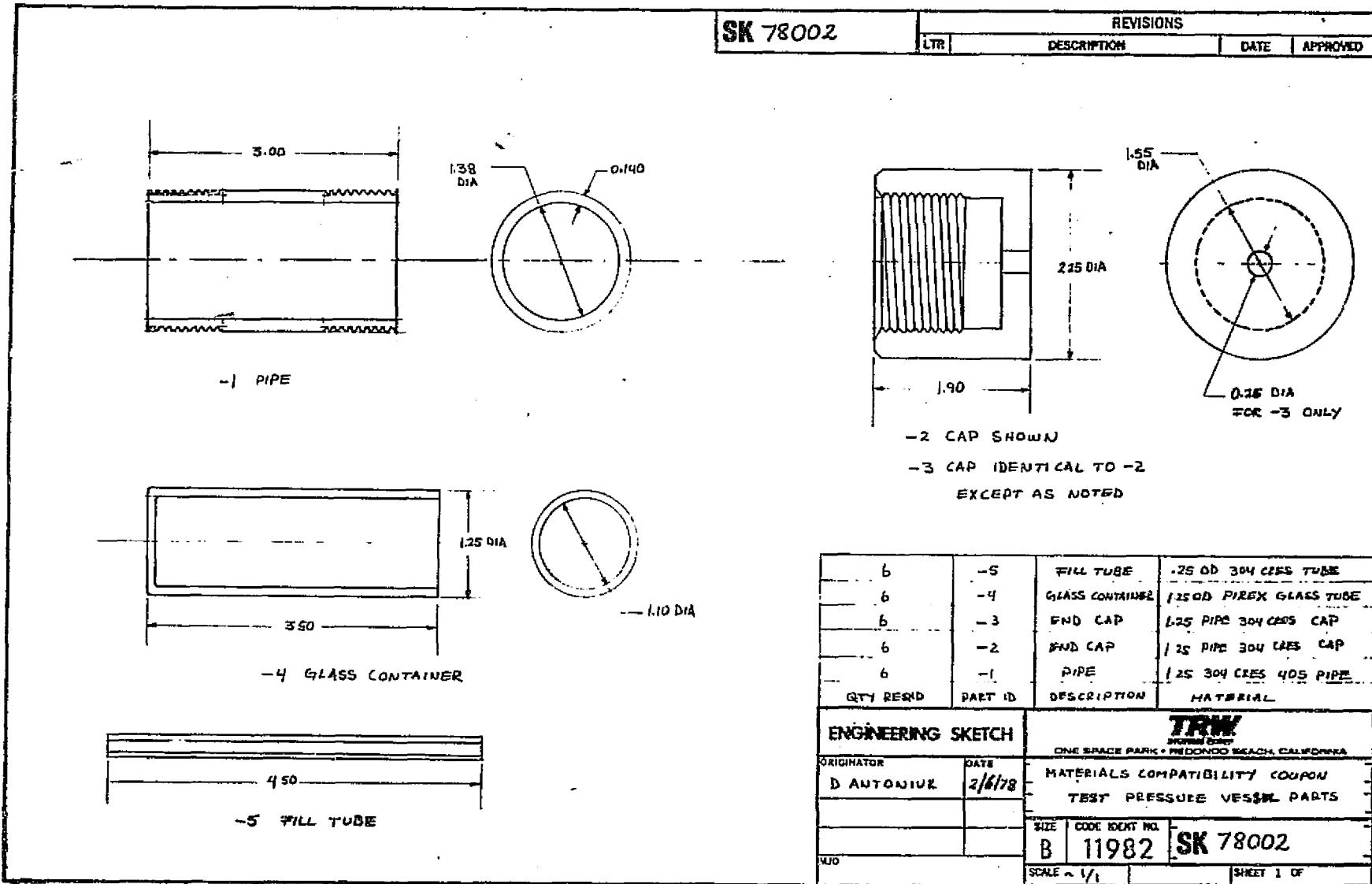


Figure 3-4. Coupon Test Pressure Vessel Components

SK 78003	REVISIONS																														
LTR	DESCRIPTION	DATE	APPROVED																												
<p>NOTES:</p> <ol style="list-style-type: none"> <input checked="" type="checkbox"/> WELD PER PR3-1 2. PRESSURE TEST AT 2000 PSI 3. SOLVENT CLEAN ALL PARTS EXCEPT SK 78001-1 AND -2 4. LEAK CHECK ASSY 																															
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 10%;">QTY REQ'D PER ASSY</th> <th style="width: 10%;">PART NO</th> <th style="width: 40%;">DESCRIPTION</th> <th style="width: 40%;">MATERIAL / SPECIFICATION</th> </tr> </thead> <tbody> <tr> <td style="text-align: center;">1</td> <td style="text-align: center;">-1</td> <td style="text-align: center;">VALVE</td> <td style="text-align: center;">304 SS $\frac{1}{4}$" 45K VALVE</td> </tr> <tr> <td style="text-align: center;">1</td> <td style="text-align: center;">SK 78002-1</td> <td style="text-align: center;">PIPE</td> <td></td> </tr> <tr> <td style="text-align: center;">1</td> <td style="text-align: center;">-2</td> <td style="text-align: center;">END CAP</td> <td></td> </tr> <tr> <td style="text-align: center;">1</td> <td style="text-align: center;">-3</td> <td style="text-align: center;">END CAP</td> <td></td> </tr> <tr> <td style="text-align: center;">1</td> <td style="text-align: center;">-4</td> <td style="text-align: center;">GLASS CONTAINER</td> <td></td> </tr> <tr> <td style="text-align: center;">1</td> <td style="text-align: center;">-5</td> <td style="text-align: center;">FILL TUBE</td> <td></td> </tr> </tbody> </table>				QTY REQ'D PER ASSY	PART NO	DESCRIPTION	MATERIAL / SPECIFICATION	1	-1	VALVE	304 SS $\frac{1}{4}$ " 45K VALVE	1	SK 78002-1	PIPE		1	-2	END CAP		1	-3	END CAP		1	-4	GLASS CONTAINER		1	-5	FILL TUBE	
QTY REQ'D PER ASSY	PART NO	DESCRIPTION	MATERIAL / SPECIFICATION																												
1	-1	VALVE	304 SS $\frac{1}{4}$ " 45K VALVE																												
1	SK 78002-1	PIPE																													
1	-2	END CAP																													
1	-3	END CAP																													
1	-4	GLASS CONTAINER																													
1	-5	FILL TUBE																													
ENGINEERING SKETCH <small>ONE SPACE PARK • REDONDO BEACH, CALIFORNIA</small> <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 30%;">ORIGINATOR</td> <td style="width: 30%;">DATE</td> <td colspan="2" style="width: 40%;">MATERIALS COMPATIBILITY TEST</td> </tr> <tr> <td>D ANTONIUK</td> <td>2/2/78</td> <td colspan="2">PRESSURE VESSEL ASSEMBLY</td> </tr> <tr> <td></td> <td></td> <td style="text-align: center;">SIZE</td> <td style="text-align: center;">CODE IDENT NO.</td> </tr> <tr> <td></td> <td></td> <td style="text-align: center;">B</td> <td style="text-align: center;">11982</td> </tr> <tr> <td>MJO</td> <td></td> <td style="text-align: center;">ROLE</td> <td style="text-align: center;">PSET 1 OF</td> </tr> </table>				ORIGINATOR	DATE	MATERIALS COMPATIBILITY TEST		D ANTONIUK	2/2/78	PRESSURE VESSEL ASSEMBLY				SIZE	CODE IDENT NO.			B	11982	MJO		ROLE	PSET 1 OF								
ORIGINATOR	DATE	MATERIALS COMPATIBILITY TEST																													
D ANTONIUK	2/2/78	PRESSURE VESSEL ASSEMBLY																													
		SIZE	CODE IDENT NO.																												
		B	11982																												
MJO		ROLE	PSET 1 OF																												

Figure 3-5. Coupon Test Vessel Assembly

possible contamination of the fluid charge stemming from impurities in or on the pressure vessel walls (photograph on page 3-10).

Prior to a test run, all vessel components were ultrasonically cleaned in an acetone bath. After inserting the coupon(s) and sealing the pressure vessel, a vacuum leak check was performed followed by a pressure test with nitrogen gas up to 1000 psia and subsequent evacuation of the gas. Finally, the refluxing mixture was transferred and the complete test assembly was immersed in a water constant-temperature bath set to control the temperature within $\pm 1^{\circ}\text{C}$.

3.2 Coupon Analysis

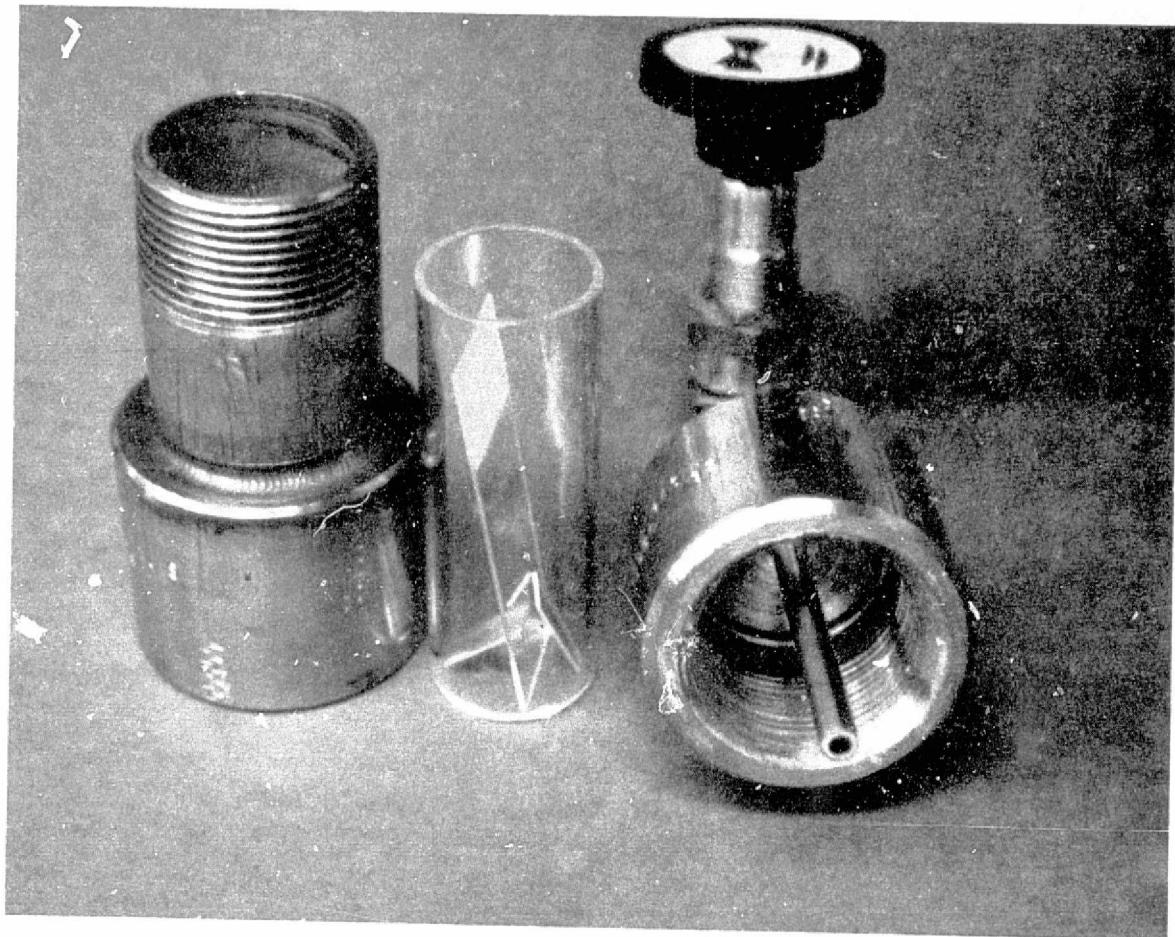
In order to determine the effects of the cleaning procedure and degree of surface passivation during refluxing, the coupons were subjected to various analyses.

3.2.1 Reflectance Measurements

Directional spectral reflectance measurements were made on coupons before and after cleaning and exposure tests. Figure 3-6 shows typical pre-cleaning reflectance data for 6061 aluminum. The raw stock was a sheet which was visibly dark, typical of aluminum with a natural oxide present, samples 1 and 2. Figure 3-7 shows the reflectance of both 5056 and 6061 after chemical cleaning. All oxide film was removed, and the spectral reflectance was visibly and measurably higher. Data for both 5056 and 6061, samples 13 and 1 and 2, respectively, after 20 hours exposure to 10.5% water/89.5% ammonia by weight at 100°C are shown in Figures 3-8, 3-9, and 3-10. The results show a marked decrease in spectral reflectance, with a large variability from point-to-point on each sample. There is a definite oxide film build-up, but it is so thin that its thickness cannot be measured by reflectance techniques.

3.2.2 Microscope Observation

Observations of the coupons surface under a stereomicroscope



Photograph Showing Components of Pressure Vessel for Coupon Exposure

ORIGINAL PAGE IS
OF POOR QUALITY

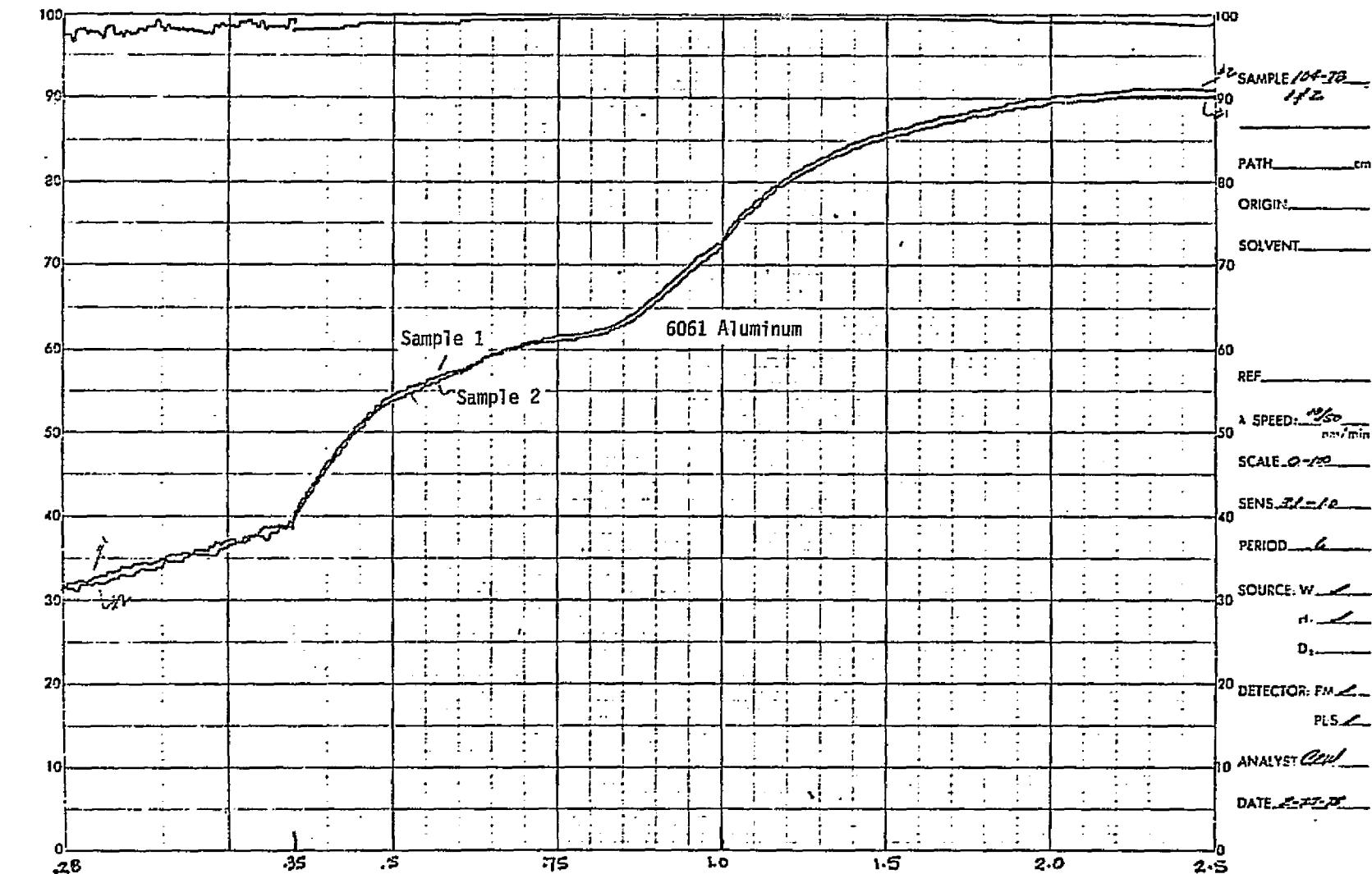


Figure 3-6. 6061 Aluminum, Samples 1 and 2, Precleaning Reflectance

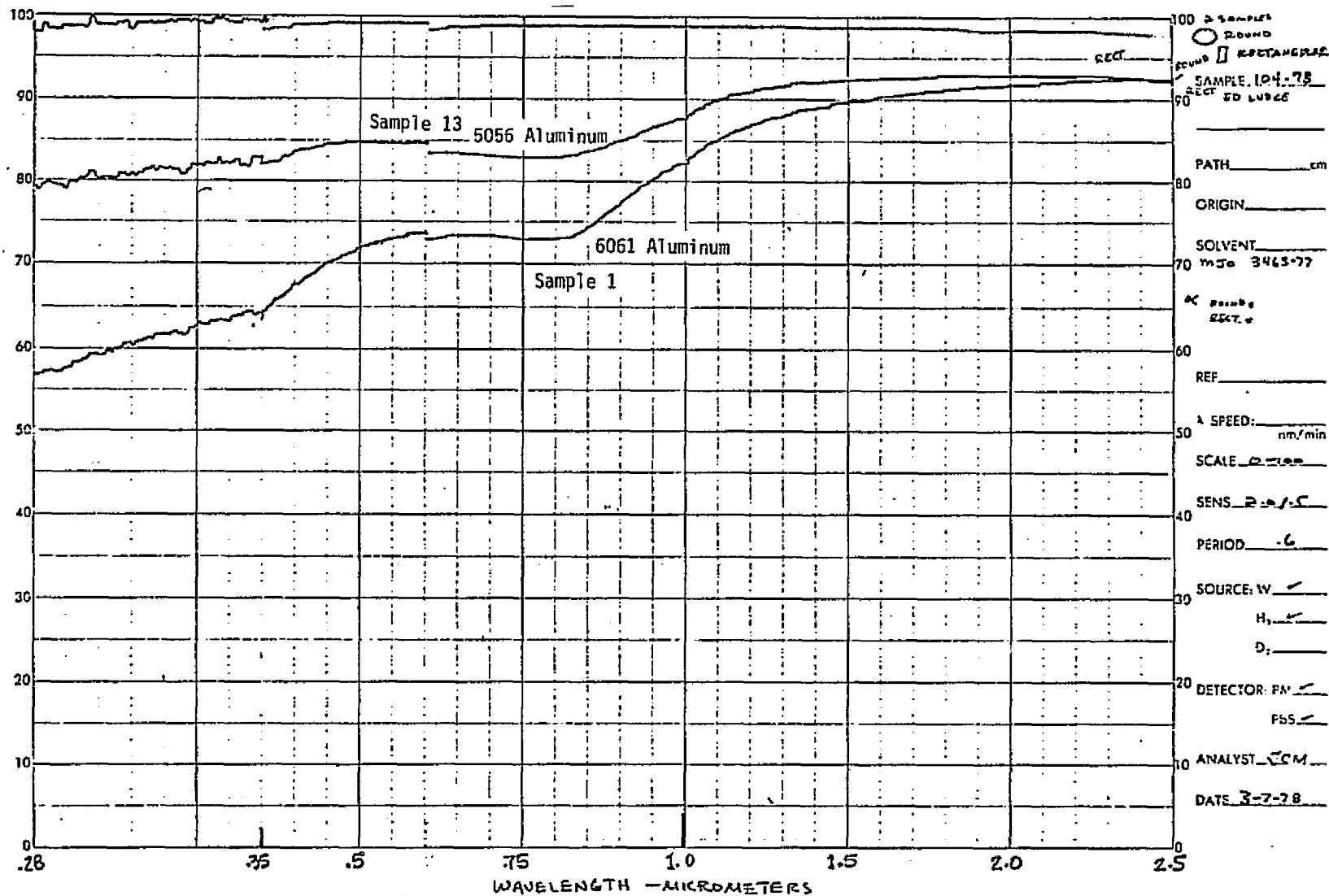


Figure 3-7. 6061 Aluminum, Samples 1 and 2, and 5056 Aluminum, Sample 13,
Pre-exposure Reflectance, Post Cleaning (Chemical)

3-13

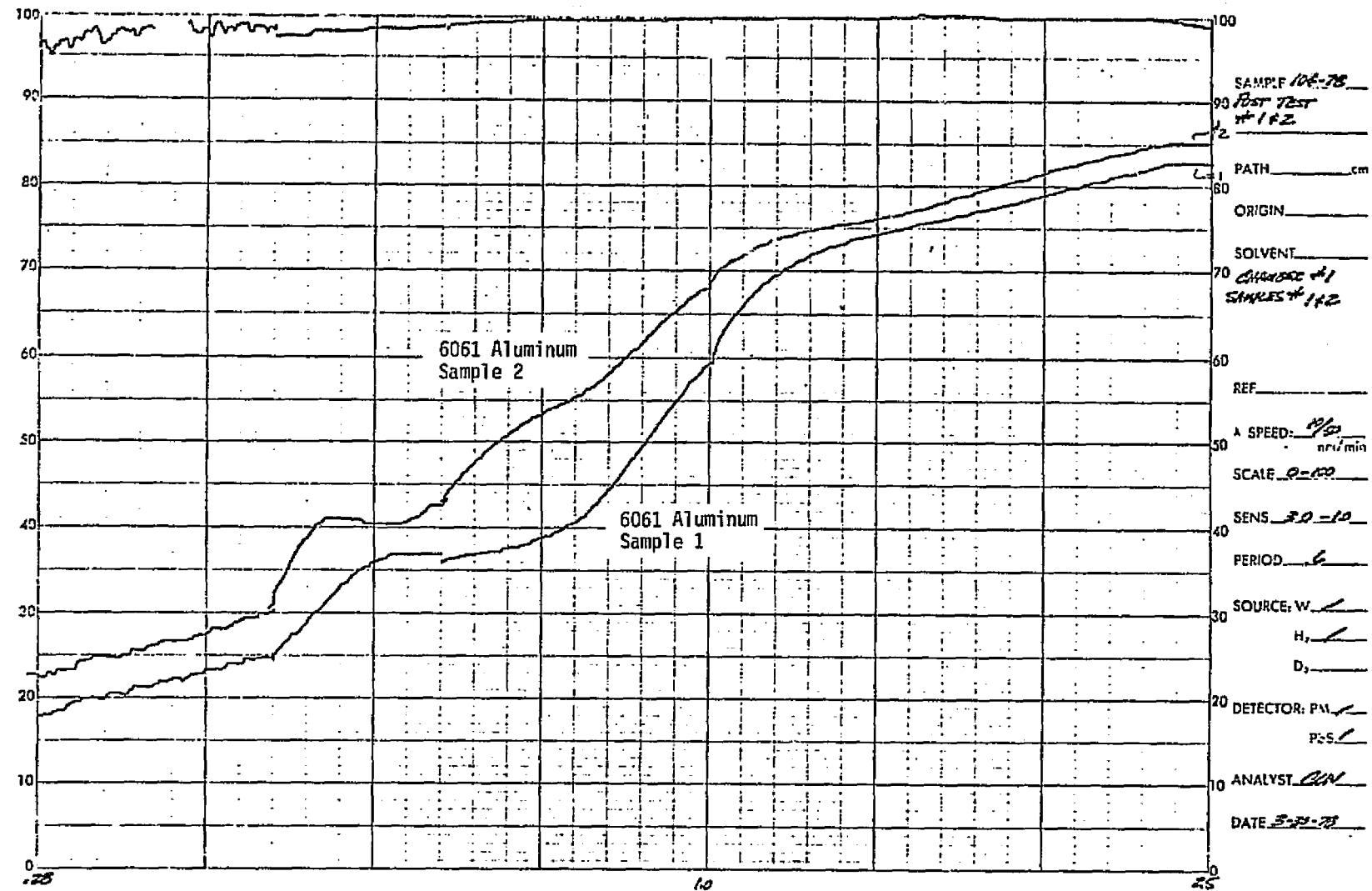


Figure 3-8. 6061 Aluminum, Samples 1 and 2, After 20 Hours Exposure to Ammonia With 10.5% Water at 100°C

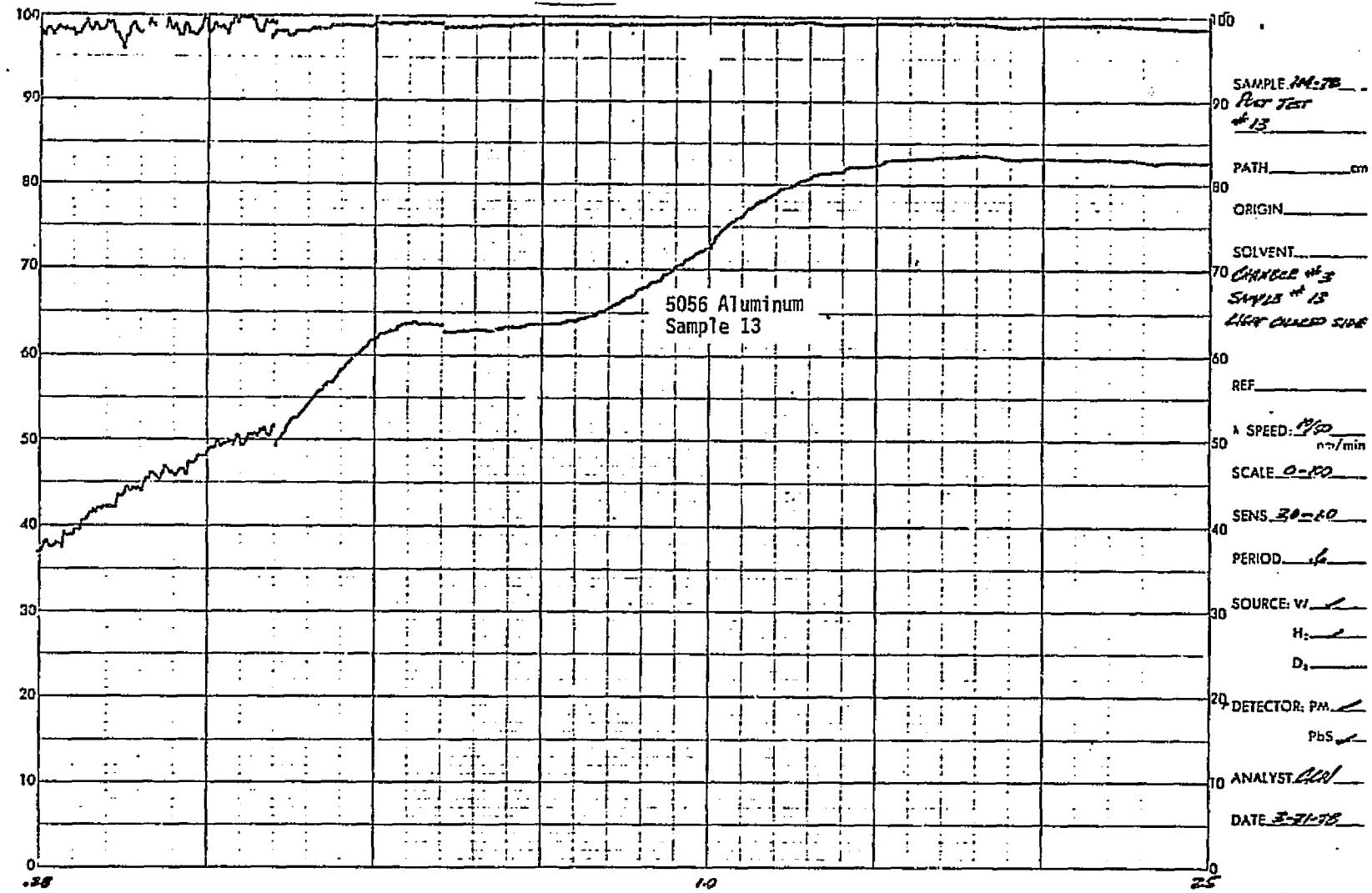


Figure 3-9. 5056 Aluminum, Light Color Side of Sample 13, After 20 Hours Exposure to Ammonia With 10.5% Water at 100°C

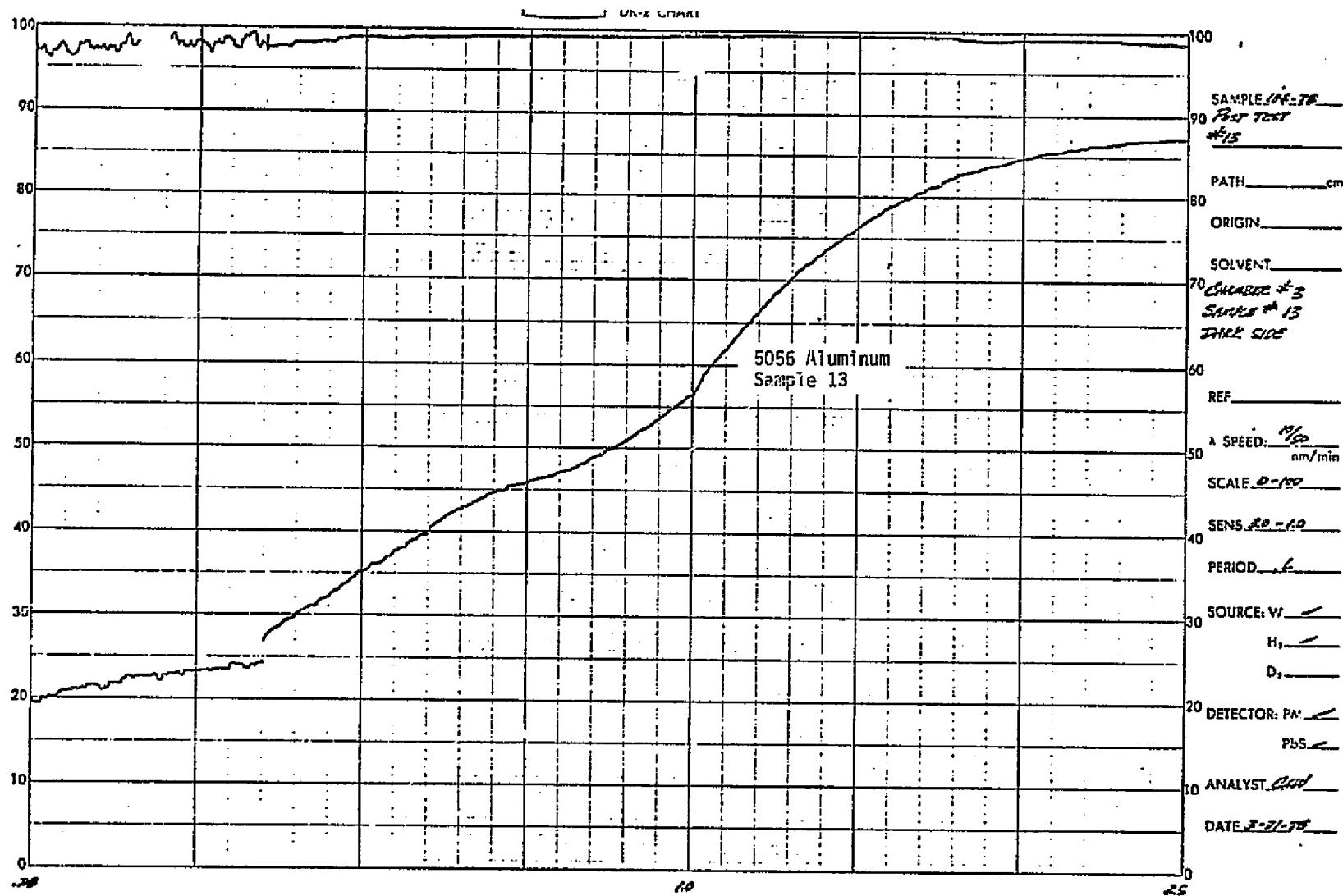


Figure 3-10. 5056 Aluminum, Dark Side of Sample 13, After 20 Hours Exposure to Ammonia with 10.5% Water at 100°C

shows distinct differences between chemically and solvent cleaned coupons, particularly before exposure. The solvent cleaned sample shows what appears to be a thin layer of corrosion which can be construed to be the result of continuous passivation of the surface during storage of the stock material in air which naturally contains water moisture. On the other hand, the chemically cleaned sample lacks this oxide layer indicating the effectiveness of the chemical procedure in removing this layer and exposing a base material surface on which cracks and fissures can be observed.

If the hypothesis that passivation of the aluminum is instrumental in reducing gas generation in heat pipes has merit, then chemically cleaning a partially passivated sample is counter-productive since the surface is "depassivated". However, it would be of great interest to determine if the presence of water during refluxing stages could restore the passivating layer on the chemically cleaned aluminum surface under more controlled conditions.

Microscopic analysis of coupons also revealed qualitative differences among coupons exposed to ammonia/water solutions of various compositions.

Test samples 15 and 16 were exposed to pure ammonia at 100°C for 20 hours. Post-test analysis of these coupons revealed some interesting results. A dark-grey deposit was observed on the bottom of the glass containers. The color of this deposit was similar to the color of numerous pits observed on the surface of the coupon. Under the microscope, these pits resemble minute "craters". The fact that great emphasis was placed on ensuring the cleanliness of the coupon's pressure vessels and the purity of the refluxing solution, it can be surmised that the sediment found in the glass container derived from the pits. Because of the relatively substantial amount of sediment accumulated over a 20 hour period, it can be conjectured that pitting of the aluminum surface was a result of a continuous, and perhaps, rapid, reaction of the ammonia with components of the aluminum alloy lattice structure.

To determine the reproducibility of the above mentioned events, four coupons made out of 6001 and 5056 aluminum, one of each solvent or chemically cleaned, were exposed to pure ammonia for 20 hours at 100°C. Post-exposure visual observation of these coupons showed no sign of pitting of the surface which had been observed on samples 15 and 16. The differing results are not understood, since the same cleaning filling and exposure procedures were followed in both cases. These results, though inconclusive, tend to give credence to the fact that there is a certain degree of "randomness" in heat pipe materials selection, fabrication and processin- interaction, as a result of which heat pipes manufactured by the same intended procedure will not necessarily yield the same long life performance.

The sediment found from samples 15 and 16 was chemically analyzed to determine its composition. Because of the small amount available, a crystallographic analysis could not be made. This analysis would have revealed the nature of the purported chemical reaction that took place. The percent by weight of the alloying elements of 6001 Al and in the sediment powder is shown in Table 3-3.

Table 3-3
CHEMICAL COMPOSITION OF SEDIMENT
FROM TEST SAMPLES NUMBER 15 AND 16

Constituents	Percent by Weight Composition of 6061 Al Alloy	Composition of Sediment
Al	98.5 - 97.25	91.72
Mg	0.80 - 1.20	3.25
Cr	0.15 - 0.35	3.46
Cu	0.15 - .40	0.88
Si	0.40 - 0.80	0.70

It is interesting to note that the relative amount of chromium in the sediment is 10 to 20 times greater than in 6061 aluminum alloy.

A photograph of sample 15 (chemically cleaned), magnified 400 times, is shown in Figure 3-11a, which distinctly points to the fact that the interaction of ammonia and the aluminum surface was not uniformly distributed but rather localized on discrete regions of the surface, presumably on regions having the largest concentration of impurities, i.e., Cr, Mg, Cu, Si.

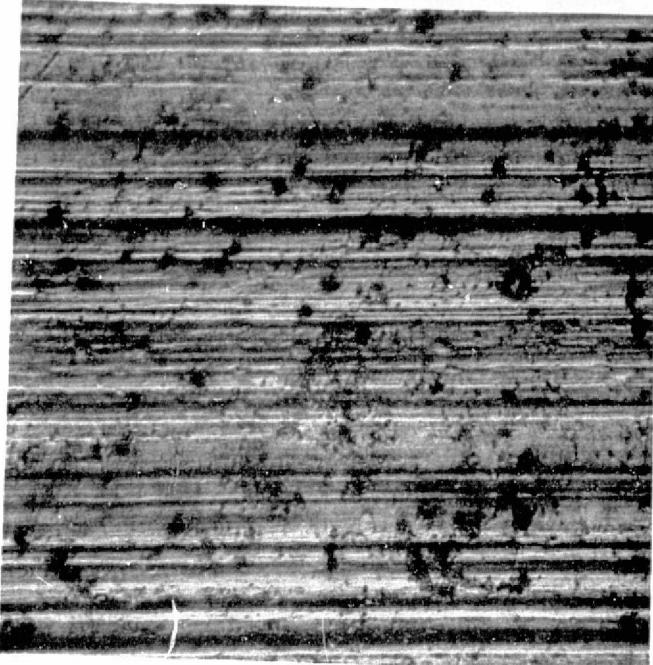
Examining Figure 3-12a and 3-12c, it can be seen that chemical cleaning effectively removes the typical oxide film present on the surface of as rolled 6061 aluminum. Figure 3-12b also shows surface pitting, which could indicate that the impurities were chemically removed, revealing a highly pure aluminum surface.

The fact that the chemical analysis in Table 3-3 shows that impurities on the chemically cleaned coupon did interact with ammonia tends to indicate that the chemical cleaning procedure is effective in removing surface impurities only to a certain extent.

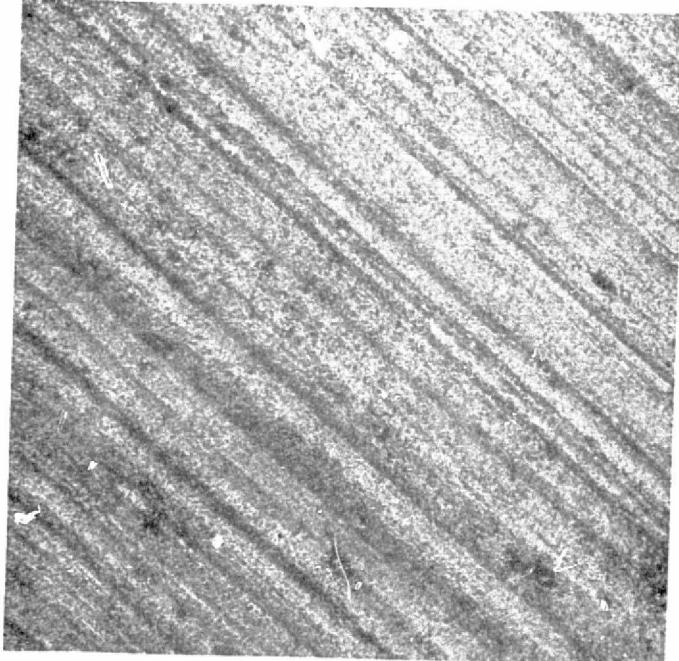
Figures 3-11b and 3-11c show that chemically cleaned surfaces in the presence of water do undergo passivation, the extent of which appears to bear some proportionately to the amount of water in the refluxing mixture. Figure 3-11c shows a smoother surface, which is believed to be the presence of a uniform oxide film.

3.3 Summary and Conclusion

Thirty coupons, 0.75" DIA x .040" thick 6061 Al and 0.75" x .375" x .03" 5056 Al, were used in a test matrix to determine the effect of two cleaning procedures, chemical and solvent, on the coupons' surface characteristics. In addition, these coupons were exposed to water/ammonia solutions at water concentrations from 0 to 10.5% and temperatures of 60° to 100°C for 5 to 100 hours

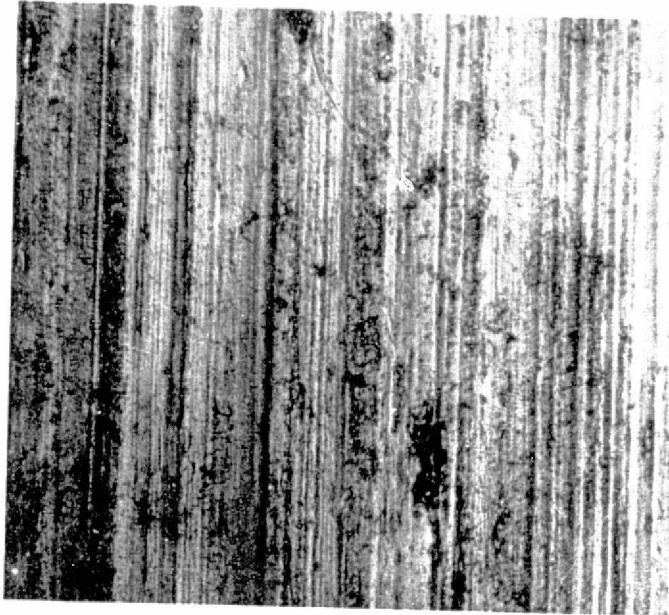


a) Sample 15 - Chemical Cleaning - 0% H₂O



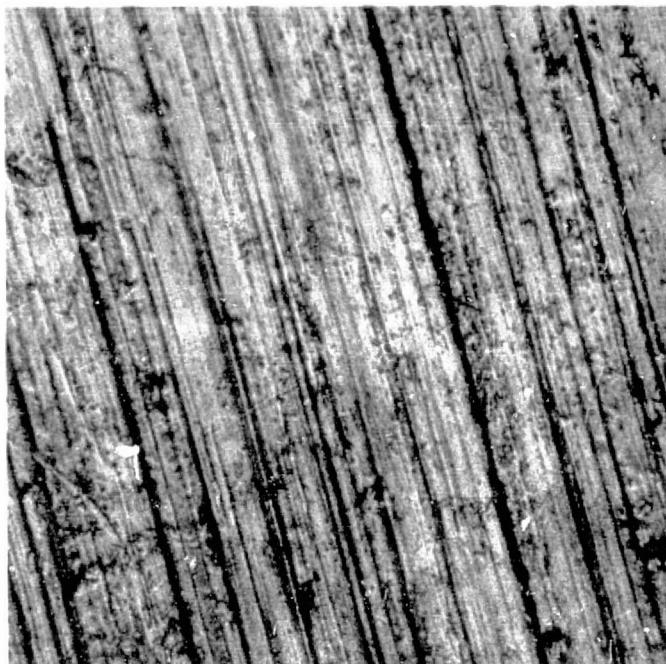
c) Sample 2 - Chemical Cleaning-10.5% H₂O

ORIGINAL PAGE IS
OF POOR QUALITY

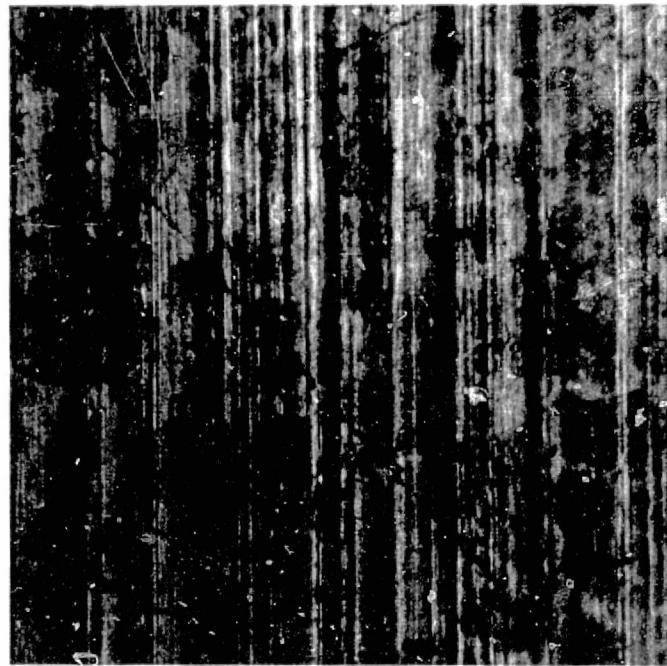


b) Sample 9 - Chemical Cleaning-0.23% H₂O

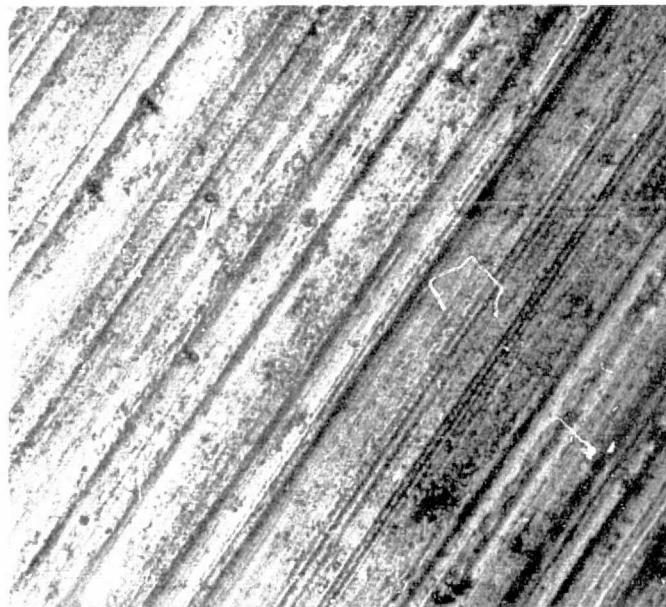
Figure 3-11. Surface of 6061 Al Coupons Magnified 400 Times



a) Reference Sample - Solvent Cleaning
(Pretest)



b) Sample 29 - Solvent Cleaning - 3% H_2O



c) Reference Sample - Chemical Cleaning
(Pretest)

Figure 3-12. Surface of 6061 Al Coupons Magnified 400 Times

4.0 PHASE II: HEAT PIPE MATRIX

The objective of this phase of the program was to subject an eighteen-heat-pipe matrix to accelerated life test at 80°C to determine the merit of the processing procedure recommended from the coupon study in fabricating heat pipes with low gas generation.

4.1 Processing Flow Chart

The recommended heat pipe processing flow chart is shown in Figure 4-1. Nine heat pipes were chemically cleaned, assembled in groups of three heat pipes and refluxed with 0% H₂O/100% NH₃, 3% H₂O/97% NH₃ and 10% H₂O/90% NH₃ by weight, respectively. A similar procedure was followed for the nine solvent cleaned heat pipes. After refluxing the heat pipes for 20 hours at 80°C, a vacuum bake step at 160°C for 16 hours was followed in order to ensure that most of the unreacted water is removed prior to the addition of the final charge of pure ammonia.

Subsequently the 18 heat pipes were subjected to accelerated life test at 80°C except for short intervals in which gas generation data were taken in a -40°C environment. One item in the flow chart differ from conventional processing procedures, namely the vacuum bake step after refluxing. Generally, the vacuum bake precedes heat pipe refluxing. The rational of this processing flow chart is based on the hypothesis that once the water has passivated the aluminum surface during refluxing, it should be removed prior to the final charge. Water remaining in the final charge might give rise to continuous gas generations reactions which certainly would be undesirable through the life of the heat pipe.

The eighteen-heat-pipe life test matrix is summarized in Table 4-1. The selection of a single life test temperature of 80°C was based on the fact that in the life test program completed under Contract NAS3-20782, a very weak correlation existed between operating temperatures of 40°, 80° and 100°C and gas generation in aluminum/NH₃ systems. As far as selecting the amount of water

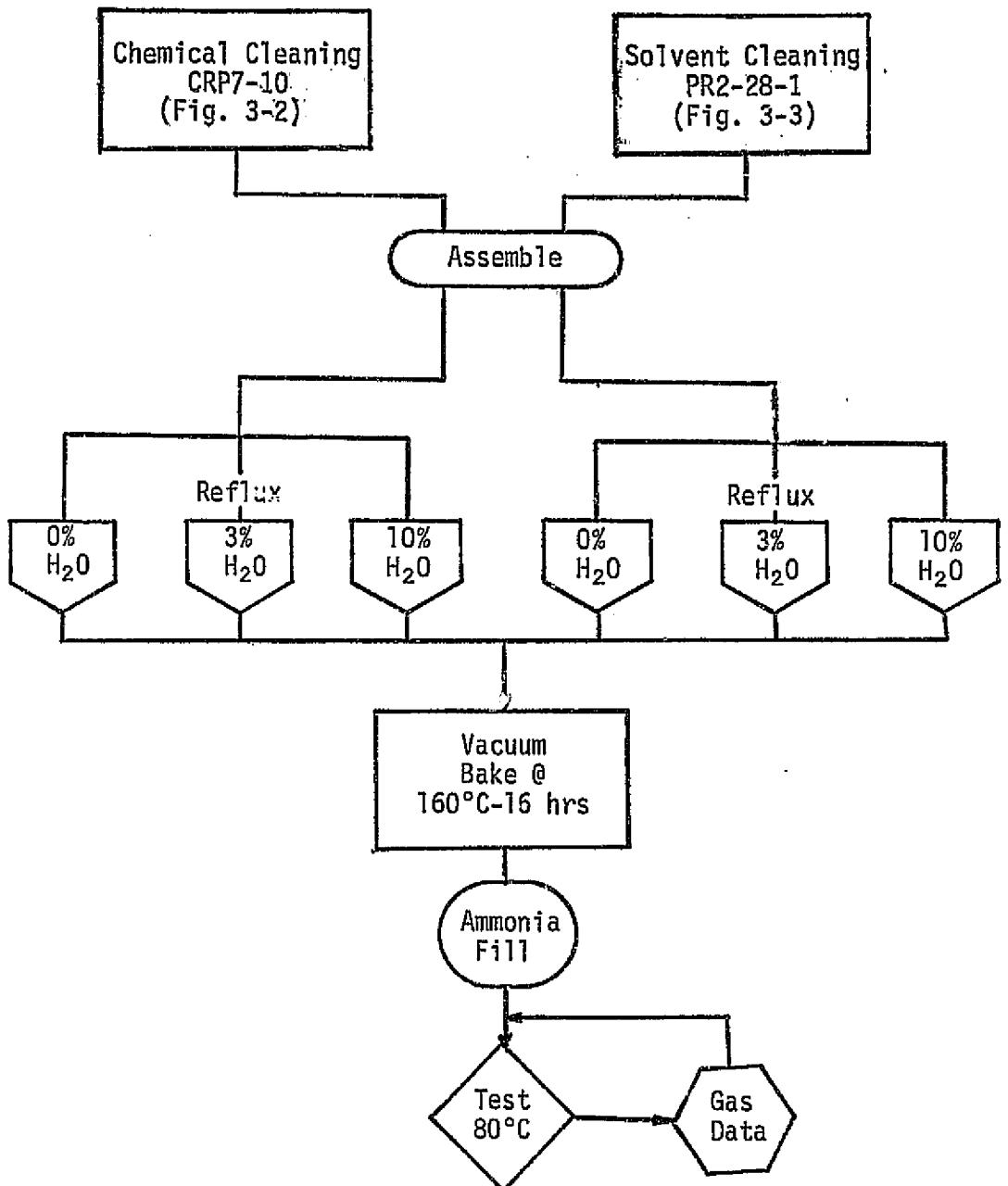


Figure 4-1. Basic Processing Flow Chart

TABLE 4-1
RECOMMENDED HEAT PIPE LIFE TEST MATRIX

Heat Pipe Serial Number	Tube Material	Wick Properties	Reflux Procedure % H ₂ O	Temp °C	Time Hrs.	Cleaning Procedure	Test Temperature °C	Remarks
1-3	6061-T6 Al Alloy	5056 Al .005 Wire Dia. 82.7% Porosity	0.0	80	16	Solvent per PR2-28-1	80	Vacuum Bake 16 hrs. @ 160°C
4-6			3.0					
7-9			10.0					
10-12			0.0			Chemical per CRP7-10		
13-15			3.0					
16-18			10.0					

4
ω

in the refluxing mixtures, engineering judgement was exercised in view of the fact that this novel approach to passivate the aluminum surface by refluxing with water is relatively new.

4.2 Heat Pipe Fabrication

The heat pipes used in this study are representative of TRW's current moderate capacity non-arterial design. As shown in Figure 4-2, they have a metal-fiber wick inside a tube that is circumferentially threaded with 100 threads per inch. The appendix contains engineering sketches for the heat pipes, their instrumentation and installation. As shown in Figure 4-3 and 4-4 each set of three identical heat pipes is mounted in common aluminum evaporator blocks. The evaporator block consists of two half saddles with three 0.5 inch diameter grooves extending the full length.

In this study, the inner section of each half saddle was lined with .001 inch thick Kapton sheet in order to electrically insulate

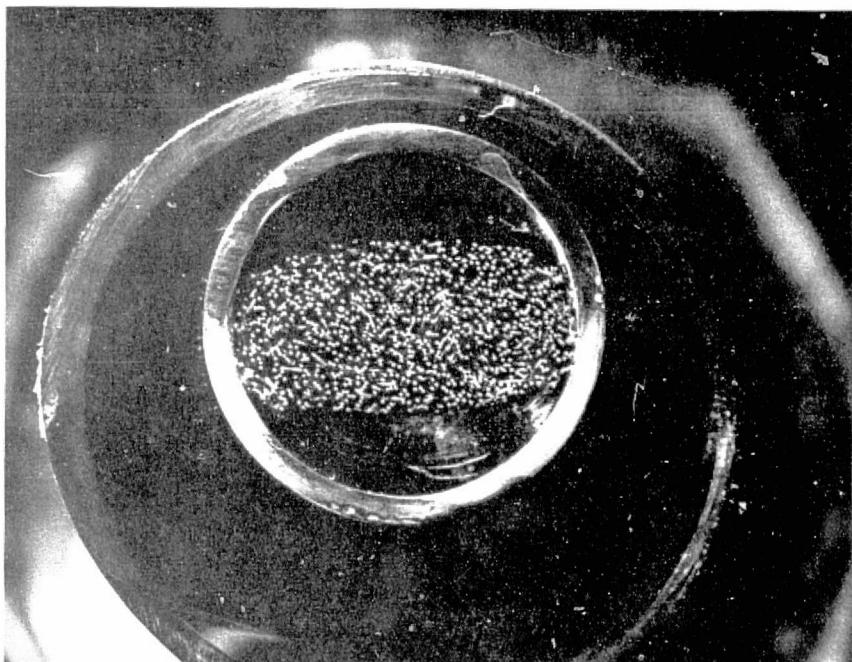


Figure 4-2. Photograph of the Cross Section of a
1.27-CM-O.D. Heat Pipe With a Metal-
Fiber Slab Wick

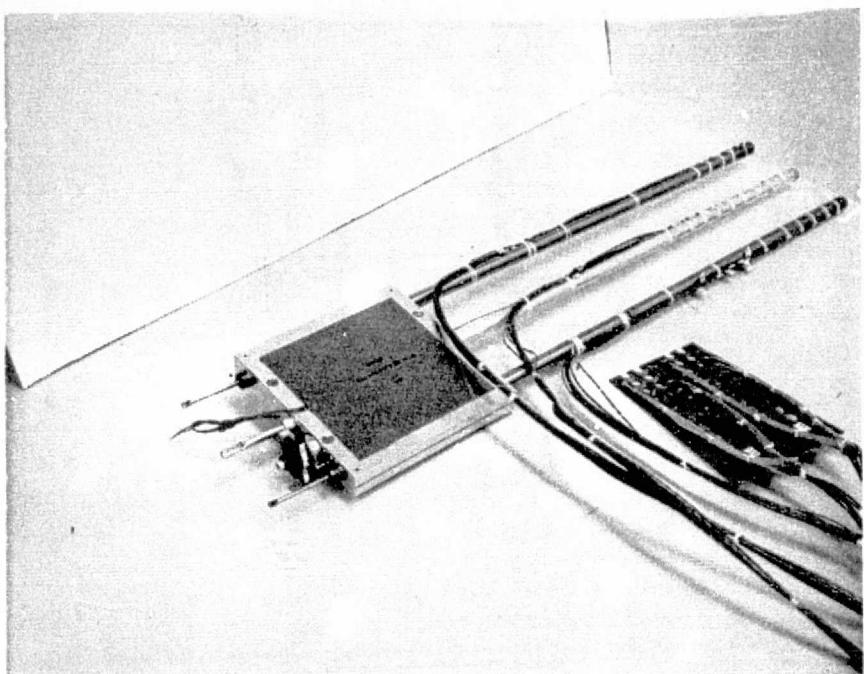
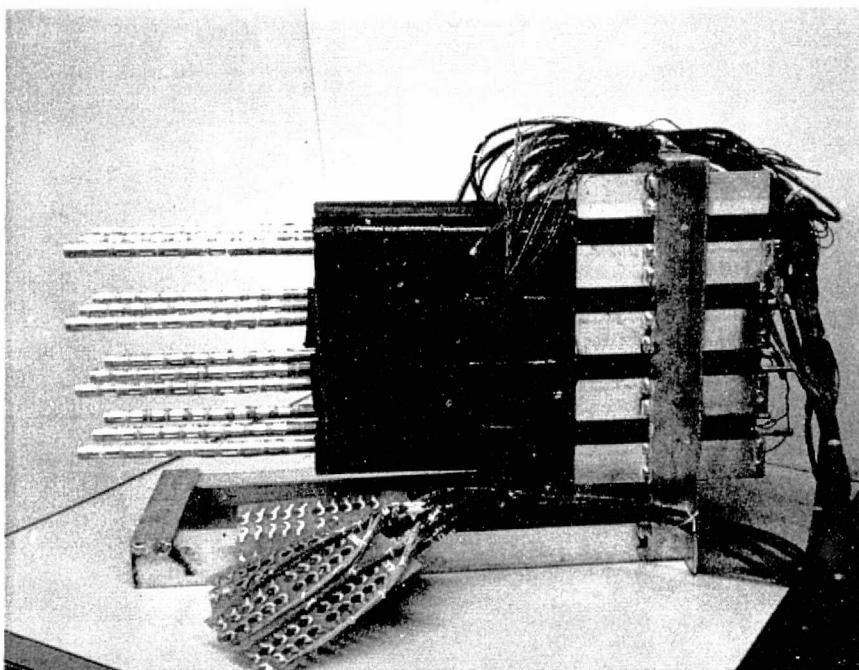


Figure 4-3. Three Heat Pipes in Common Evaporator Block With Instrumentation



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 4-4. Four Sets of Three Heat Pipes in Mounting Rack

the heat pipes from the heaters on top of the evaporator saddle. This technique avoids electrical interference with the thermocouples.

Each heat pipe is instrumented with 11 chromel-alumel thermocouples. Nine are spaced at equal intervals along the condenser section and two are in the adiabatic region. The thermocouple spacing was obtained by analysis to optimally characterize the anticipated temperature profiles. In this current study, the heat pipe configurations in previous life tests was modified to include a 4.5 - 5.0 inch wickless section at the end of the condenser section. A shorter slab wick was used to allow the gas measurements to be made in this wickless tube section. The absence of the wick in this section reduces the uncertainty in determining the vapor-gas space volume which should result in more accurate gas evaluation measurements.

The shorter wick, however, requires operation and testing of the heat pipes in a slight reflux mode.

The new heat pipe modification and thermocouple layout are shown schematically in Figure 4-5.

4.3 Heat Pipe Processing And Fill

The eighteen heat pipes were processed per the processing flow chart shown in Figure 4-1. The final charge for each heat pipe consisted of 18.6 to 19.5 grams of 99.9996% pure ammonia.

4.4 Calculation Of Gas Inventories

Except when the temperature profiles are measured at low temperatures, the heat pipes are run continuously at their operating temperature of 80°C in a slight reflux mode.

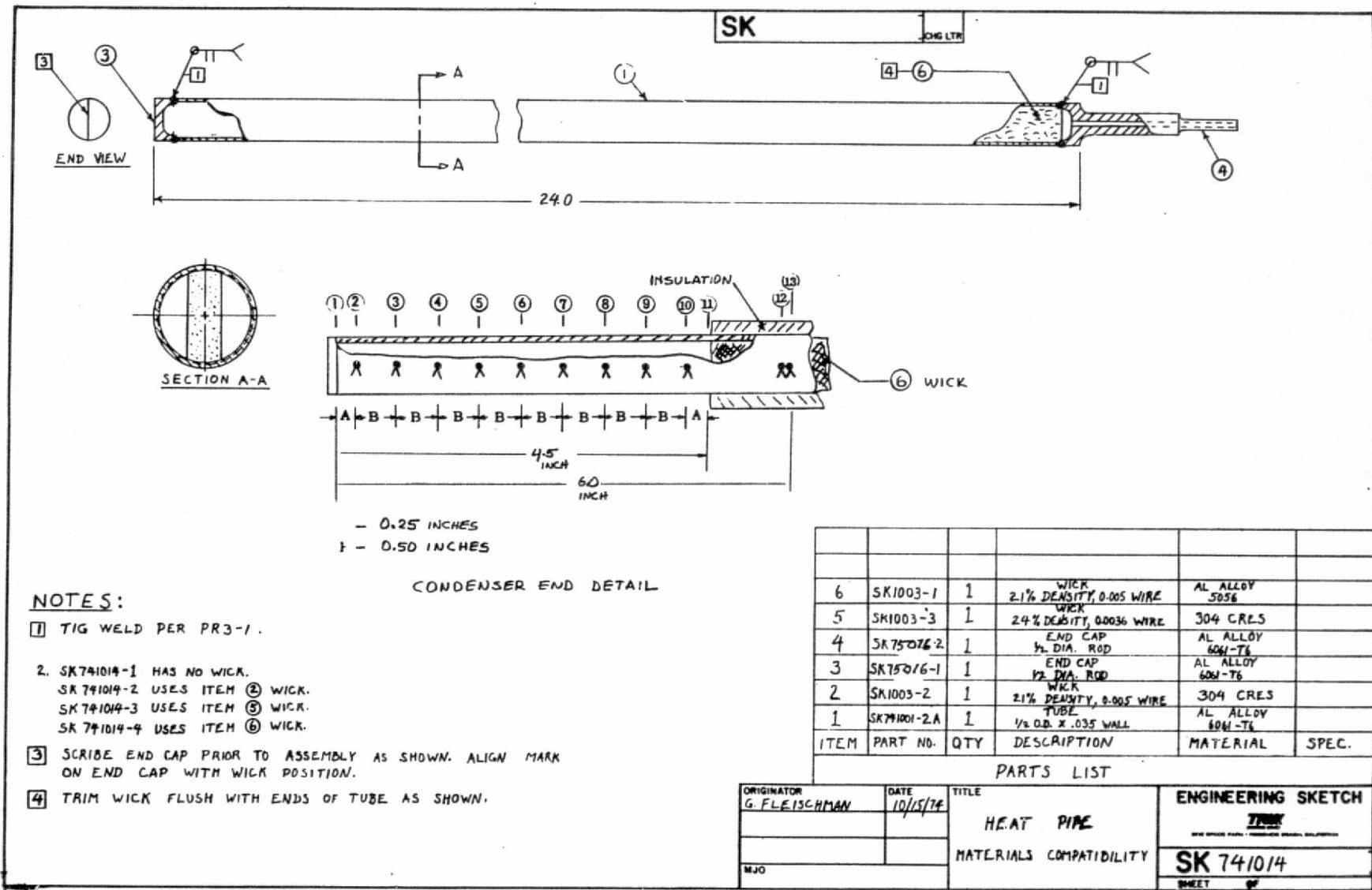


Figure 4-5. Wickless Condenser Configuration

Periodically, the heat input to the heater blocks is adjusted to maintain the required operation temperature. The heat pipes are protected from over-temperature excursion by a bi-metallic thermostat (Klixon) which is located on each evaporator block.

As non-condensable gas is evolved during operation of a heat pipe, it is carried to the condenser end causing a blockage. The typical approach is to calculate the quantity of non-condensable gas from the temperature profile of the condenser sections. The temperature profile is measured with the heat pipe operating in -40°C environment, which is provided by a low temperature environment chamber where thermal dissipation occurs by natural convection.

In the chamber, the heat pipe, under no power, isothermalizes to the environmental temperature and the gas expands to fill the entire heat pipe.

As power is applied and vapor flow from the evaporator to the condenser occurs, the gas is compressed into the wickless condenser section. A common practice is to adjust the power (or vapor pressure) until TC 9 and TC 10 are uniform within thermocouple error. Such a condition would indicate that the non-condensable gas is contained in the wickless condenser section. A typical temperature profile in the condenser is shown in Figure 4-6.

For calculation of the quantity of gas, the condenser region is divided in N intervals, and the temperature at the center of the i^{th} interval is denoted T_i . The number of moles n of non-condensable gas is given by the ideal gas law as

$$n = \frac{1}{R} \sum_{i=1}^N \frac{P_{g,i} \Delta V_i}{T_i} \quad 4.4.1$$

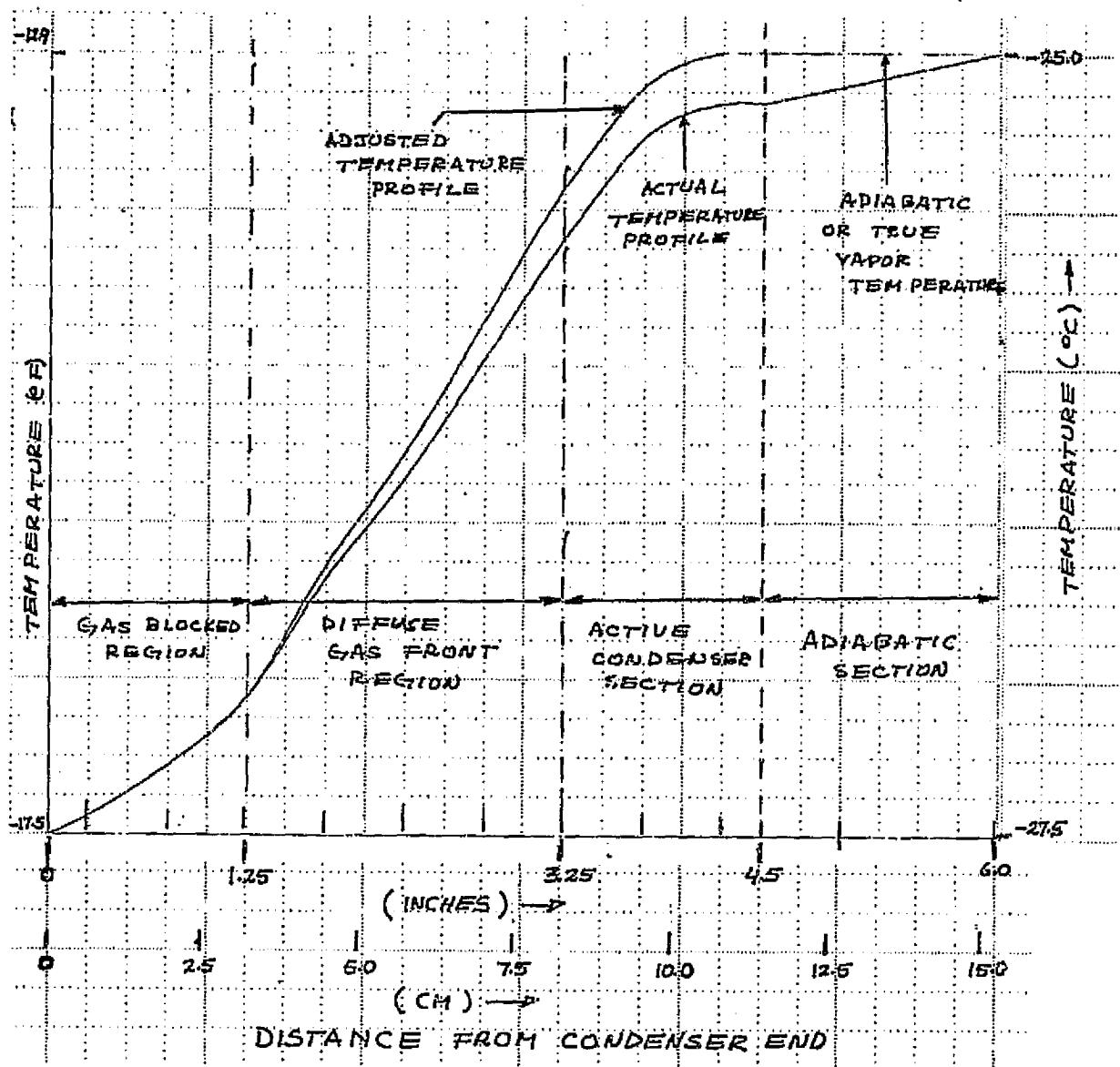


Figure 4-6. Actual And Adjusted Temperature Profiles In Condenser Section

ORIGINAL PAGE IS
OF POOR QUALITY

where ΔV is volume of each interval available for gas and vapor and R is the universal gas constant. The partial pressure of the gas, $P_{g,i}$ is given by

$$P_{gi} = P_{va} - P_{v,i} \quad 4.4.2$$

where

$$P_{v,a} = P_v (T_{adiabatic}) \quad 4.4.3$$

which in our configuration

$$P_{v,a} = P_v (T_{v,12})$$

$$\text{and } P_{v,i} = P_v (T_{v,i}) \quad 4.4.4$$

where $T_{v,i}$ and $T_{v,12}$ are the temperatures at the liquid film - vapor interface. In the current heat pipe thermocouple layout, the temperature profile along the heat pipe represents the profile along the outer wall of the pipe, i.e. $T_{w,i}$, temperatures that depart from temperatures at the liquid-vapor interface except in the adiabatic region and in the gas blocked region where no condensation heat transfer takes place. Hence, respectively:

$$T_{w,12} = T_{v,12}$$

$$\text{and } T_{w,i} = T_{v,i}$$

Referring to Figure 4-6, in the active condenser section and diffuse gas front region

$$T_{w,i} \neq T_{v,i}$$

Consequently, $T_{v,i}$'s have to be obtained by extrapolation from the temperatures at the outer wall of the pipe.

Before attempting to adjust these temperatures, it is necessary to determine the domain of the three regions in the condenser section.

In this study, we took the following engineering approach to define the domain of the three regions in the condenser section. Define a temperature difference ΔT_L as:

$$\Delta T_L = T_{w,11} - T_{w,1} \quad 4.4.5$$

where $T_{w,1}$ and $T_{w,11}$ have been extrapolated to the end of the condenser ($z = 0$) and the beginning of the condenser ($z = 4.5$ in.) by a quadratic interpolation scheme. A second temperature difference is then defined as:

$$\Delta T_U = 0.2 * \Delta T_L \leq 1.5^\circ F \quad 4.4.6$$

Now, all the temperatures in the gas blocked region that are within ΔT_U are considered temperatures of the gas blocked region. Similar rational is applied to the condenser active section. Mathematically the above can be stated as:

$$\Delta T_{i,1} = T_i - T_1 \quad i = 1, 11 \quad 4.4.7$$

$$N_L = i - 1 \text{ for } \Delta T_{i,1} > \Delta T_U \quad 4.4.8$$

$$T_{11} - T_i = \Delta T_{11,i} \quad i = 1, 11 \quad 4.4.9$$

$$N_U = i \quad \text{for } \Delta T_{11,i} \leq \Delta T_U \quad 4.4.10$$

Thus, the gas blocked region incorporates temperatures

$$T_i = T_{v,i} \quad i = 1, N_L \quad 4.4.11$$

and, the active section incorporates temperatures

$$T_i = T_{w,i} \quad i = N_U, 11 \quad 4.4.12$$

All other temperatures fall within the diffuse gas front region.

In order to extrapolate the temperatures at the outer wall of the pipe to the liquid-vapor interface in the active condenser region, it is considered reasonable to use the temperature difference between $T_{v,12}$ and $T_{w,11}$, i.e.

$$\Delta T_{w,v} = T_{v,12} - T_{w,11} \quad 4.4.13$$

which is then used to adjust

$$T_{w,i} \quad i = N_U, 11 \text{ as follows}$$

$$T_{v,i} = T_{w,i} + \Delta T_{w,v} \quad i = N_U, 11 \quad 4.4.14$$

The remaining task is to adjust the temperature in the diffuse gas front region. We assume a linear correction or extrapolation in this case. Mathematically it can be stated as follows:

$$T_{v,i} = T_{w,i} + \Delta T_{w,v} \left(\frac{i - N_L}{N_U - N_L} \right), \quad i = N_L, N_U \quad 4.4.13$$

The above shows that largest temperature correction is made to the temperature adjacent to the active condenser temperatures. This adjustment diminishes to zero as the gas blocked region is reached. Having adjusted the temperature profile along the condenser section we can now proceed to calculate a more realistic gas inventory,

$$n = \sum_{i=1}^{11} \frac{(P_{v,12} - P_{v,i})}{R T_{g,i}} \times \Delta V_i \quad 4.4.14$$

To effect the above procedure, a Fortran IV computer code was written which in addition to adjusting the temperature profiles, plots the actual and adjusted data and performs the calculation of the gas inventory using a Simpson Rule integrating subroutine. A typical output from this program is shown in Figure 4-6 and Table 4-2. Figure 4-6 shows the actual and adjusted temperature profiles. Table 4-2 shows a print out containing a list of the temperature as a function of location in the condenser, and the calculated gas inventories based on actual and adjusted temperature profiles. As seen the calculated gas inventory based on actual temperature profile is the largest of the two values for reasons that were discussed above.

4.5 Heat Pipe Matrix Test Results

The test results reported in this section were obtained over a period of 283 days during which the heat pipe test matrix was subjected to accelerated life tests at an operating temperature of 80°C. The first gas inventory calculations were made approximately two weeks after the heat pipes were loaded with the final ammonia charge. During this period, the heat pipes were instrumented with thermocouples and assembled in the test fixture. Thus, the first data reflects the gas generated in two weeks during which the heat pipe test matrix can be considered to have been in storage at room temperature. Non-condensable gas inventory measurements and calculations were performed on at least nine occasions during the entire test period.

4.5.1 Individual Test Results

The gas inventories of the individual heat pipes calculated on the basis of raw data is presented in Table 4-3. As shown, heat pipe SN 06 exhibited an unusually high initial gas inventory. This could be the results of many factors. However, it will be shown that a processing error is a likely cause. Failure to close the valve after the vacuum bake operation would have allowed air to leak in and fill the pipe.

Table 4-2. Calculated Temperature Profile and Gas Inventories

HEAT PIPE NUMBER = 15
DATA TAKEN ON 03/26/79

DISTANCE FROM CONDENSER END (INCH)	ACTUAL TEMPERATURES (F)	CORRECTED TEMPERATURES (F)
0.000	-17.512	-17.512
.250	-17.400	-17.400
.750	-17.100	-17.100
1.250	-16.700	-16.700
1.750	-16.000	-15.925
2.250	-15.400	-15.250
2.750	-14.700	-14.475
3.250	-14.000	-13.700
3.750	-13.400	-13.100
4.250	-13.200	-12.900
4.500	-13.200	-12.900
5.000	-12.900	-12.900

Calculated Gas Inventories

GAS BASED ON ACTUAL TEMPERATURES = 1.0550E-07 LB-MOLES

GAS BASED ON ADJUSTED TEMPERATURES = 9.8921E-08 LB-MOLES

Table 4-3

QUANTITY OF GAS GENERATED THOUGHOUT THE LIFE TEST
BASED ON THE AVERAGE OF RAW DATA

Heat Pipe Serial Number	DAYS FROM INITIAL GAS MEASUREMENTS (LB-MOLE)								
	0	40	76	103	146	176	209	264	283
1	1.67 E-7	2.14 E-7	3.30 E-7	3.35 E-7	2.62 E-7	3.76 E-7	4.14 E-7	4.27 E-7	4.49 E-7
2	1.0 E-7	1.62 E-7	2.62 E-7	3.07 E-7	3.22 E-7	3.44 E-7	3.63 E-7	4.16 E-7	3.59 E-7
3	3.11 E-7	4.82 E-7	6.69 E-7	7.08 E-7	7.28 E-7	6.70 E-7	7.46 E-7	7.80 E-7	7.75 E-7
4	3.95 E-7	7.28 E-7	8.79 E-7	8.68 E-7	9.01 E-7	8.47 E-7	9.18 E-7	6.21 E-7	9.53 E-7
5	2.65 E-7	3.20 E-7	3.78 E-7	4.31 E-7	4.68 E-7	4.53 E-7	4.23 E-7	4.42 E-7	4.32 E-7
6	6.66 E-6								
7	3.89 E-7	4.32 E-7	3.68 E-7	4.85 E-7	5.15 E-7	4.32 E-7	4.88 E-7	4.61 E-7	5.1 E-7
8	7.1 E-7	7.16 E-7	7.87 E-7	8.55 E-7	8.92 E-7	1.0 E-6	1.03 E-6	1.17 E-6	1.16 E-6
9	4.25 E-7	1.48 E-7	4.70 E-7	4.89 E-7	5.46 E-7	5.0 E-7	4.23 E-7	7.51 E-7	6.08 E-7
10	1.17 E-7	1.31 E-7	1.31 E-7	1.62 E-7	2.19 E-7	2.36 E-7	3.51 E-7	-	1.9 E-7
11	8.42 E-8	1.05 E-7	1.58 E-7	1.86 E-7	2.21 E-7	2.03 E-7	2.94 E-7	-	2.14 E-7
12	1.29 E-7	1.18 E-7	1.3 E-7	1.64 E-7	2.47 E-7	2.38 E-7	4.04 E-7	-	2.18 E-7
13	7.7 E-9	1.42 E-7	2.08 E-7	2.18 E-7	2.32 E-7	2.34 E-7	2.18 E-7	2.42 E-7	2.35 E-7
14	2.50 E-8	2.74 E-8	3.66 E-8	4.55 E-8	7.60 E-8	7.85 E-8	1.06 E-7	1.01 E-7	1.11 E-7
15	3.98 E-8	3.46 E-8	4.07 E-8	4.60 E-8	6.74 E-8	6.52 E-8	1.13 E-7	9.90 E-8	1.10 E-7
16	1.78 E-8	8.22 E-8	8.36 E-8	1.19 E-7	1.87 E-7	2.57 E-7	5.57 E-7	5.39 E-7	6.35 E-7
17	1.45 E-8	2.76 E-8	3.90 E-8	4.12 E-8	5.01 E-8	4.92 E-8	6.16 E-8	6.34 E-8	7.21 E-8
18	1.22 E-8	3.06 E-8	4.48 E-8	4.87 E-8	4.46 E-8	5.05 E-8	6.38 E-8	7.22 E-8	8.01 E-8

Assuming this event occurred, it can be calculated that the 1b moles of air in the pipe is 5×10^{-6} which agrees quite closely with the calculated gas inventory shown in Table 4-3. As the result of its high gas inventory, heat pipe SN 06 was removed permanently from the life test matrix.

The data in Table 4-3 have been plotted as a functions of days in operation in Figures 4-7a through 4-23a.

Multiple data points for a given day represent gas inventories calculated from temperature profiles in the condenser section at various adiabatic temperatures. As seen in the figures, most of the heat pipes show what could be considered a typical scatter of the data as far as similar patterns were observed in previous materials compatibility studies.

Some heat pipes, however, evidence data at various points of life test that significantly depart from the quasi-established temporal behavior of the gas inventories.

This is the case, particularly, with heat pipes SN 10, SN 11 and SN 12 on day 209. This significant scatter of the data motivated a post examination of the test fixture in which these three heat pipes are assembled. It was found that a pin which holds the test fixture level with respect to the three-heat-pipe holding fixture, had come loose causing the condenser end of these heat pipes to tip downward. During the temperature measurement operation, the heat pipes were thus inadvertently operated in a heat pipe mode. Since all the heat pipes have a wick-less condenser section, this mode of operation caused the fluid to accumulate at the end of the pipes resulting in an unusually high adiabatic temperature and low condenser temperature profiles. This led to calculations of unreal large gas inventories.

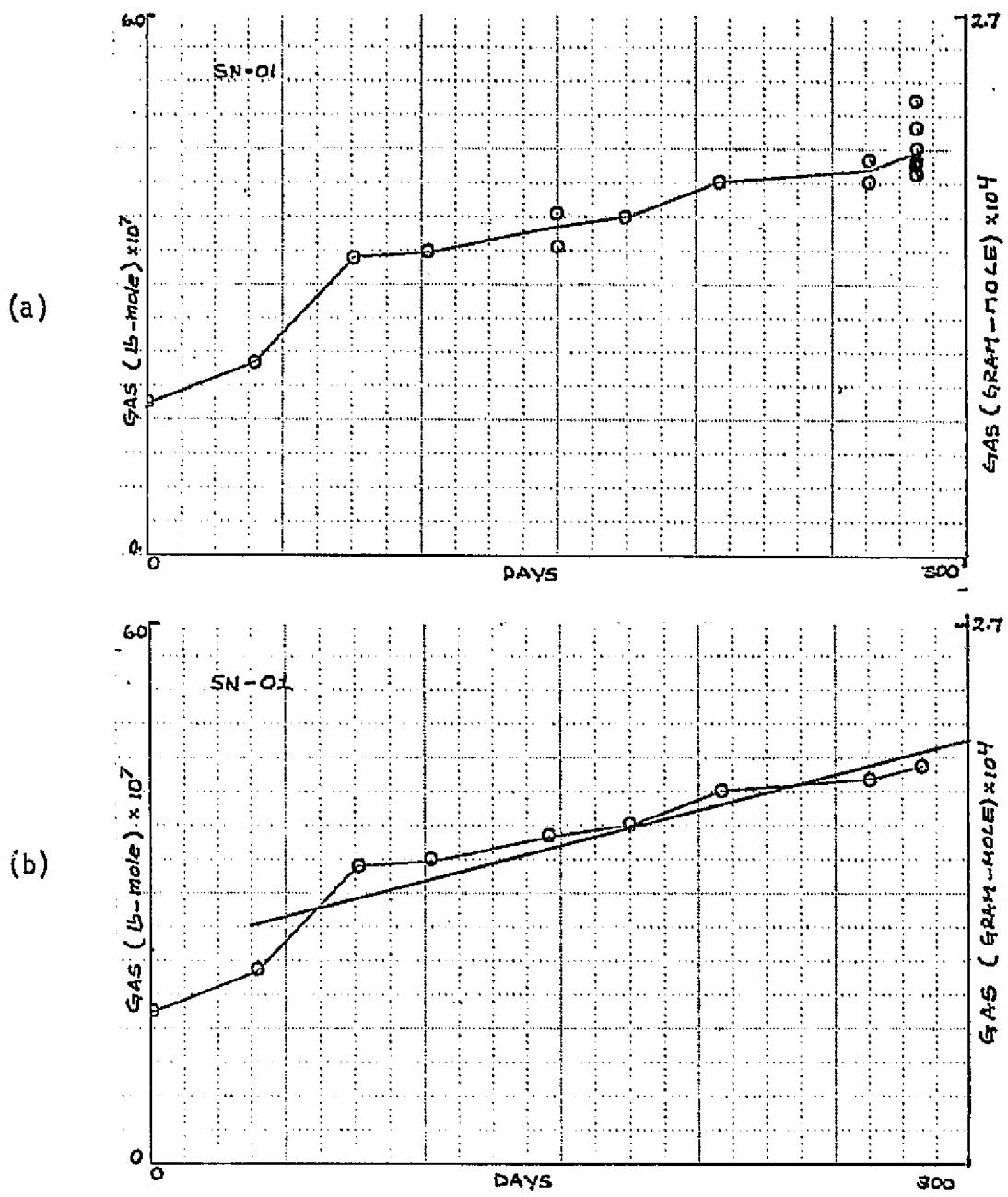


Figure 4-7. Gas Generation Data for Heat Pipe SN-01. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

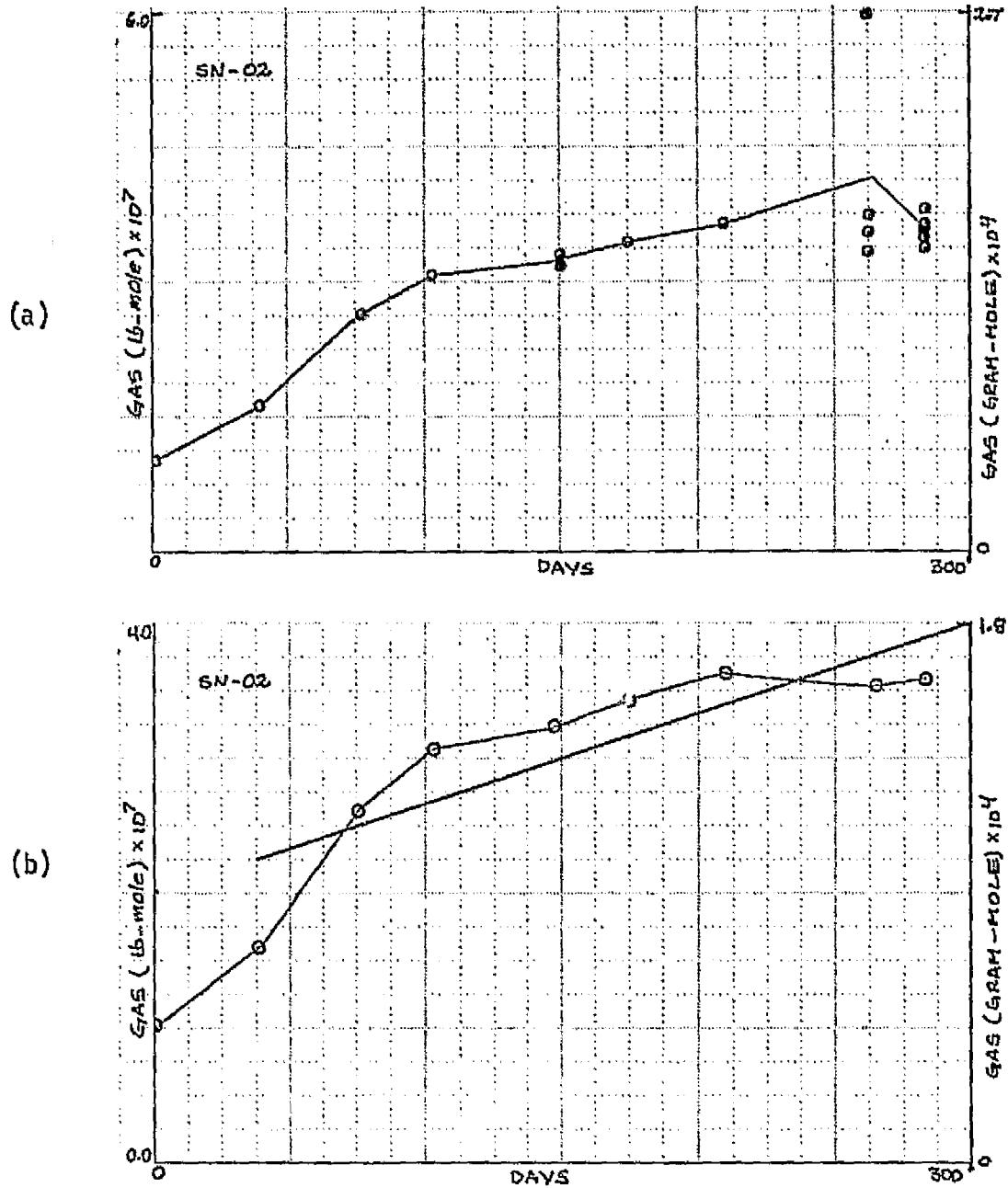


Figure 4-8. Gas Generation Data for Heat Pipe SN-02. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

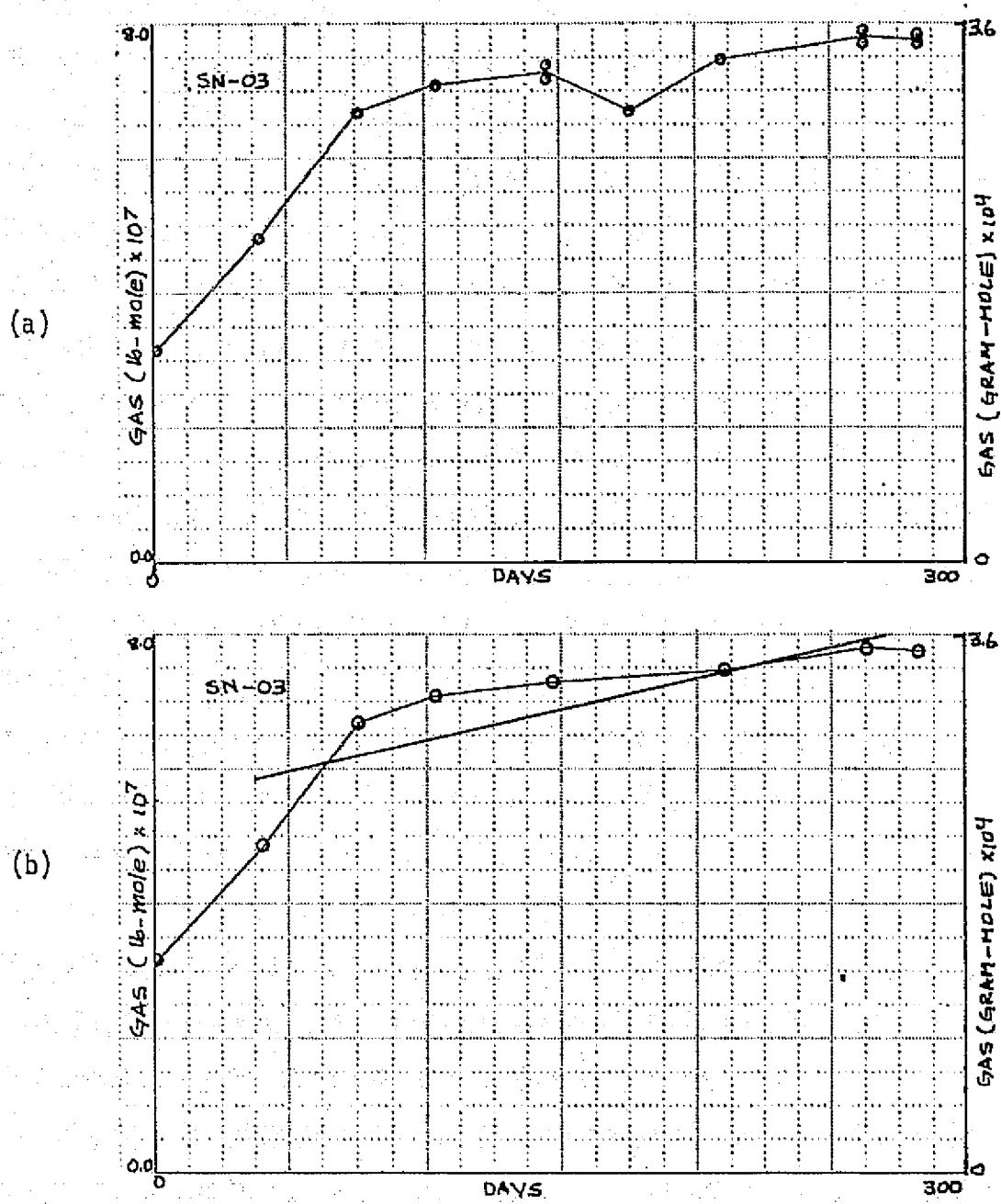


Figure 4-9. Gas Generation Data for Heat Pipe SN-03. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

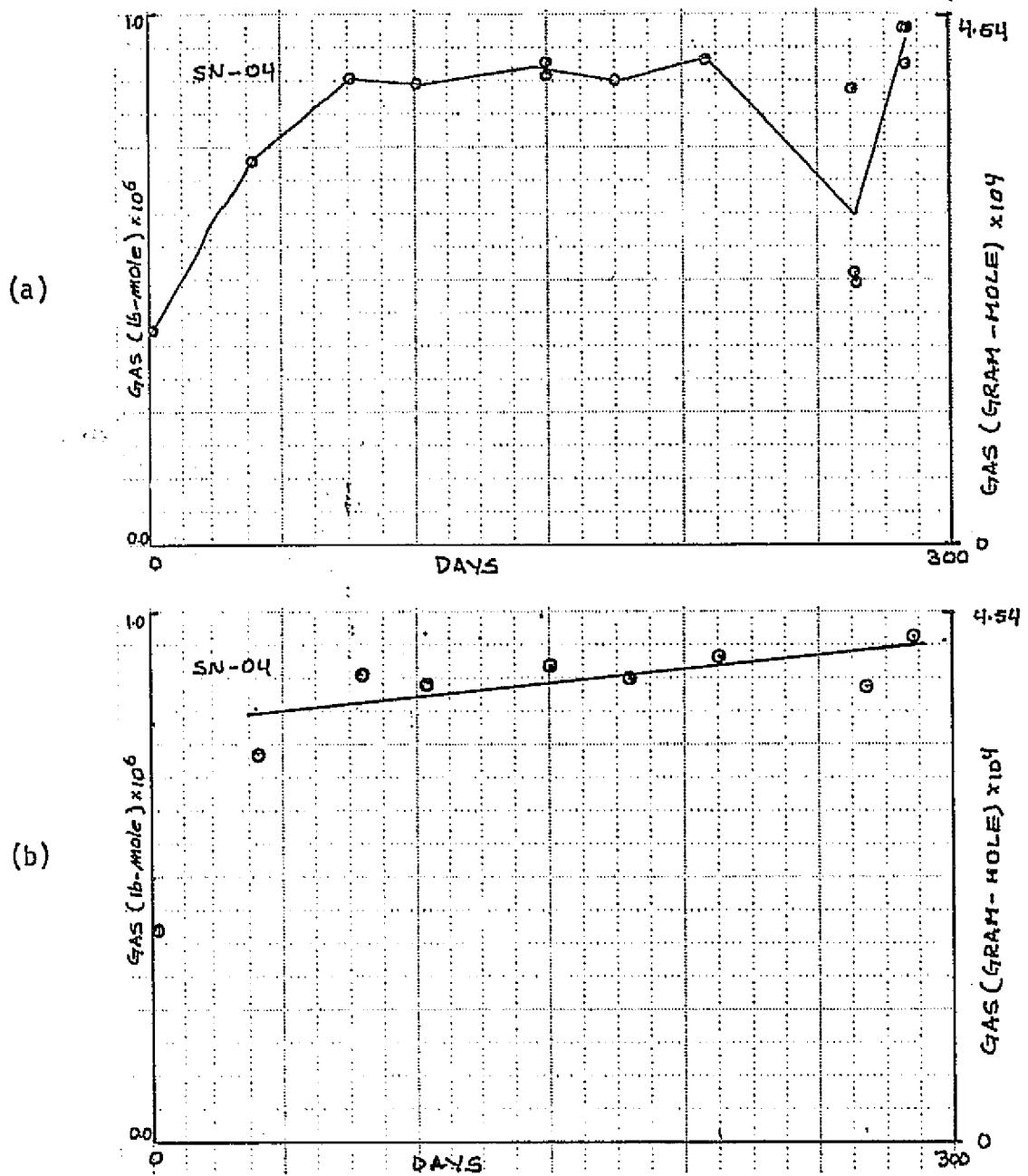


Figure 4-10. Gas Generation Data for Heat Pipe SN-04. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

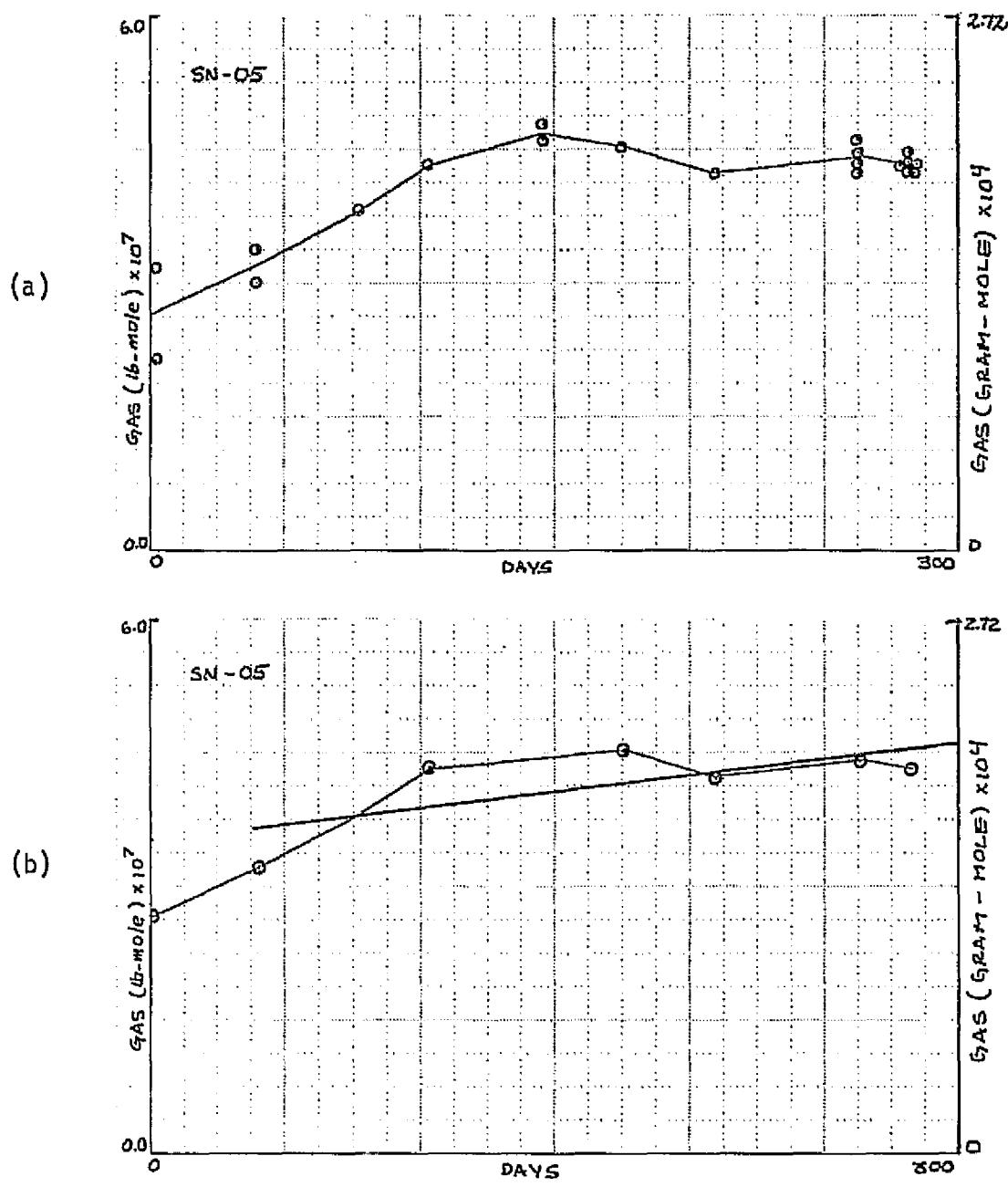


Figure 4-11. Gas Generation Data for Heat Pipe SN-05. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

ORIGINAL PAGE IS
OF POOR QUALITY

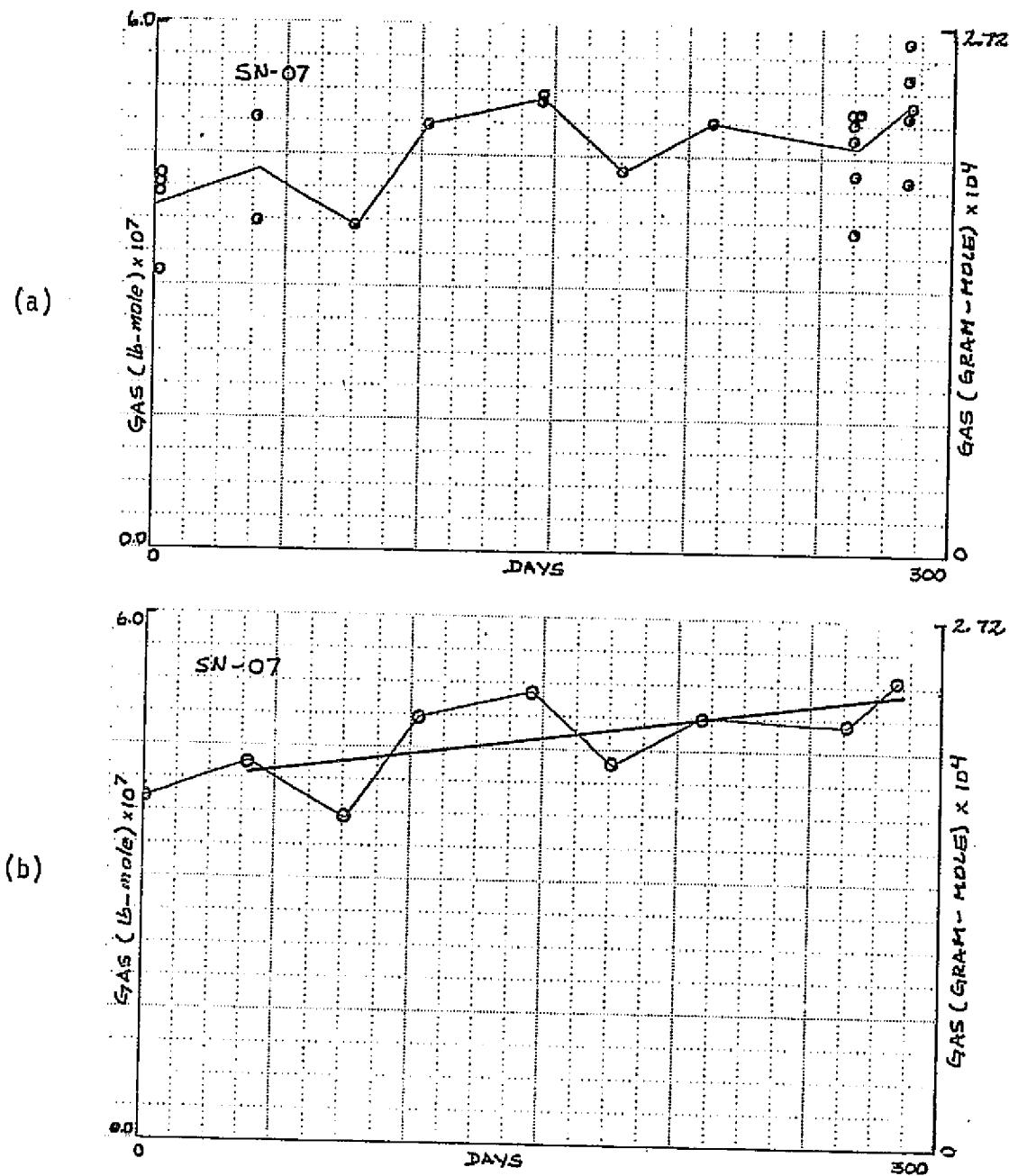


Figure 4-12. Gas Generation Data for Heat Pipe SN-07. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

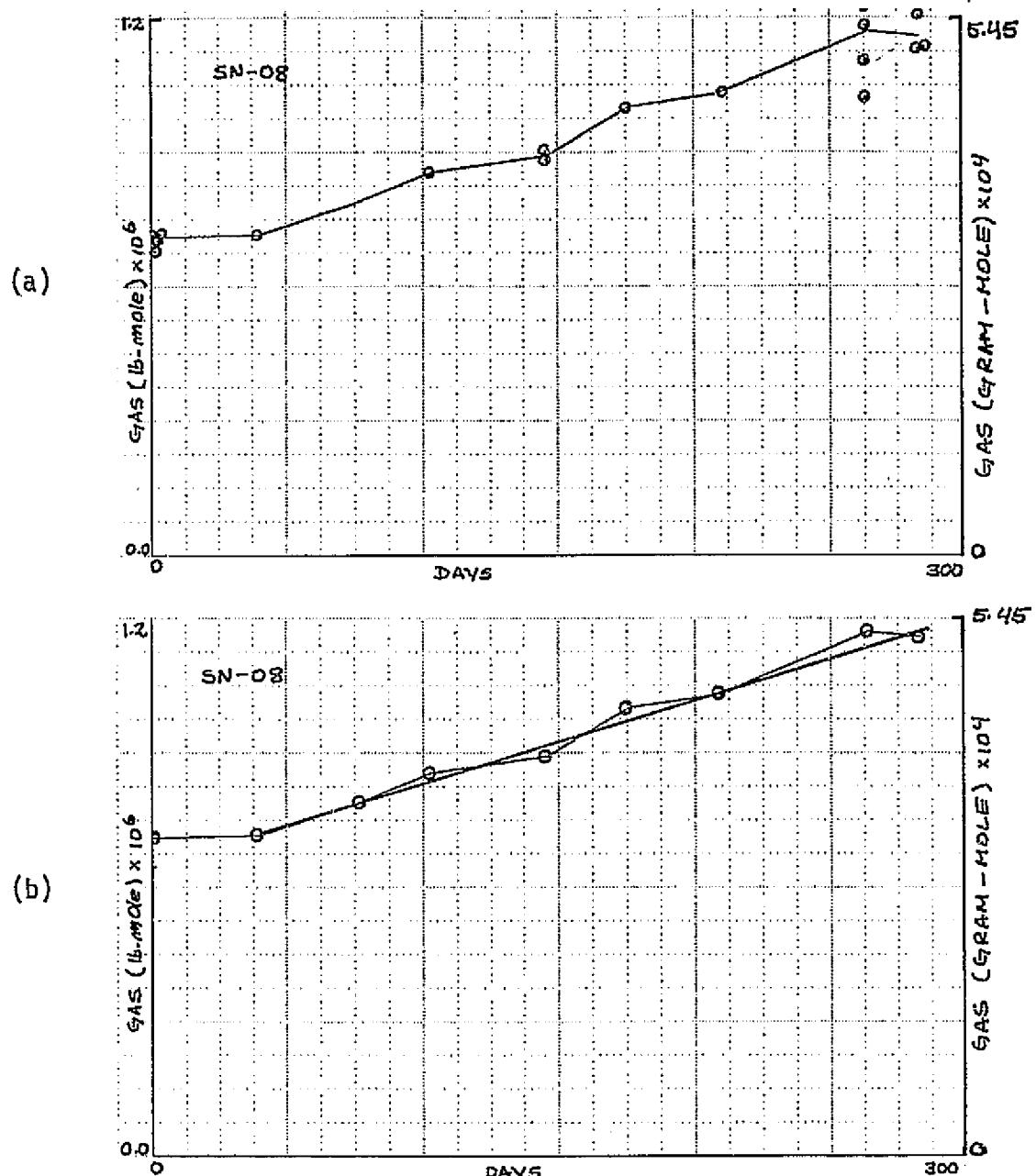


Figure 4-13. Gas Generation Data for Heat Pipe SN-08. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

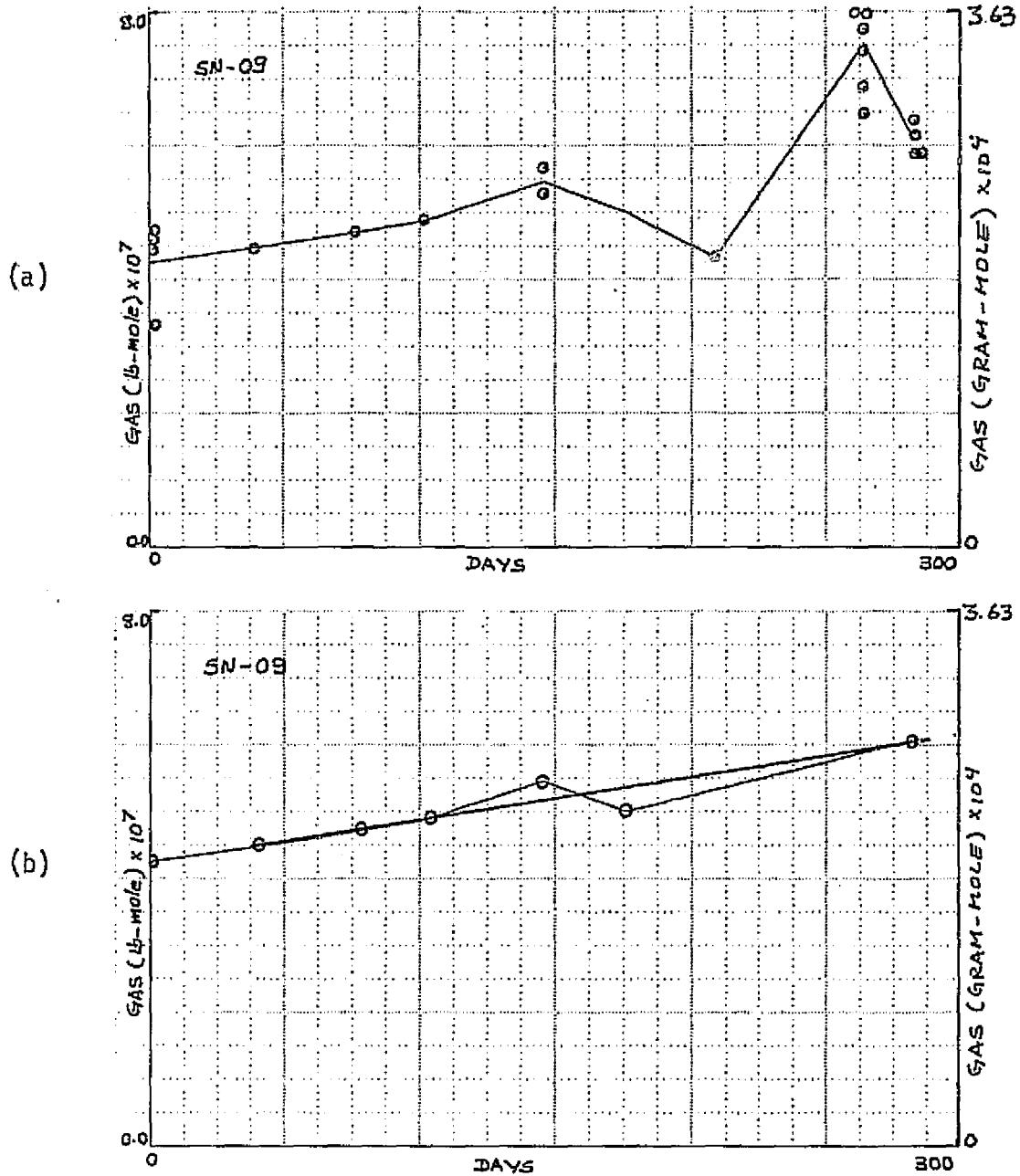


Figure 4-14. Gas Generation Data for Heat Pipe SN-09. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

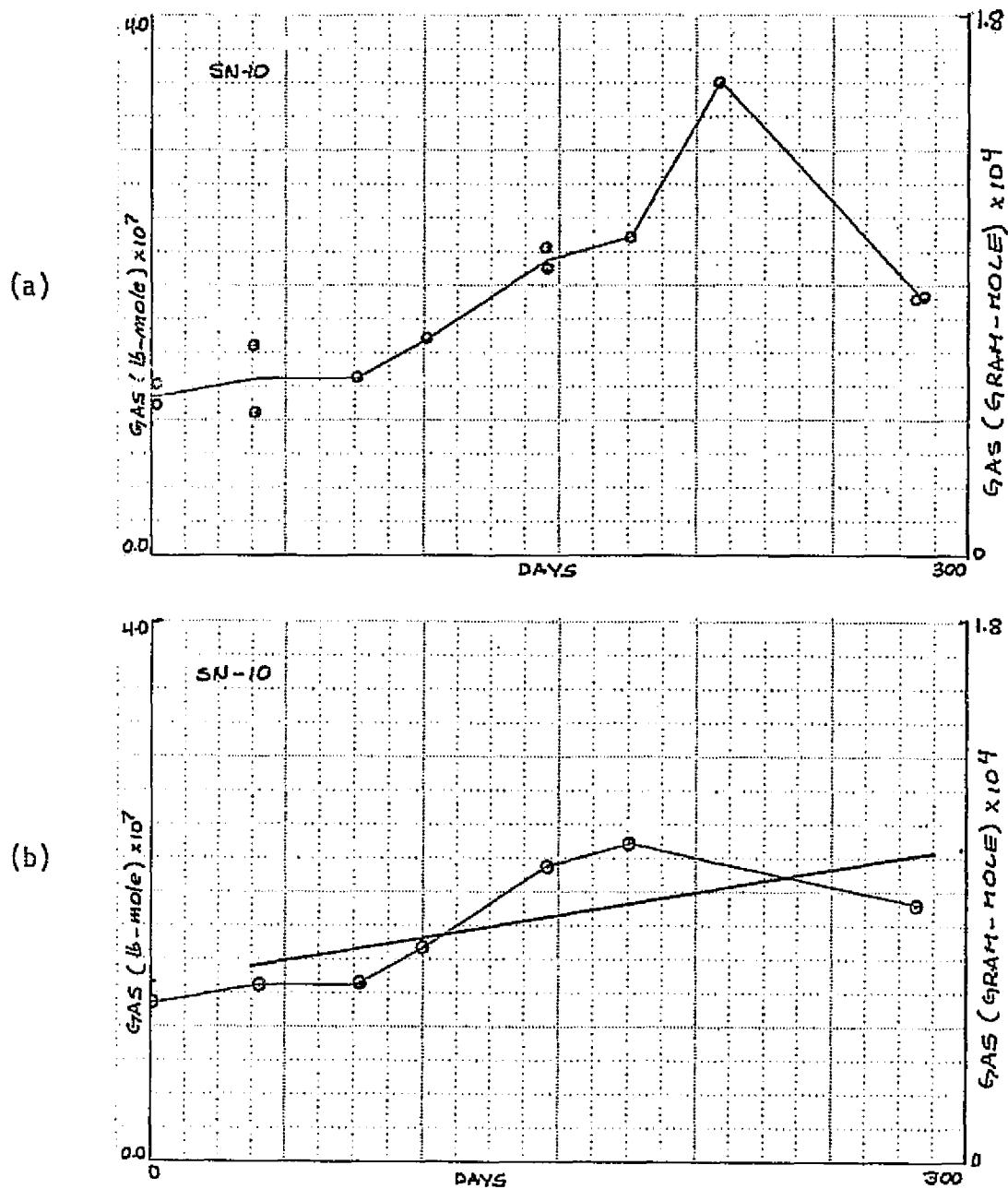


Figure 4-15. Gas Generation Data for Heat Pipe SN-10. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

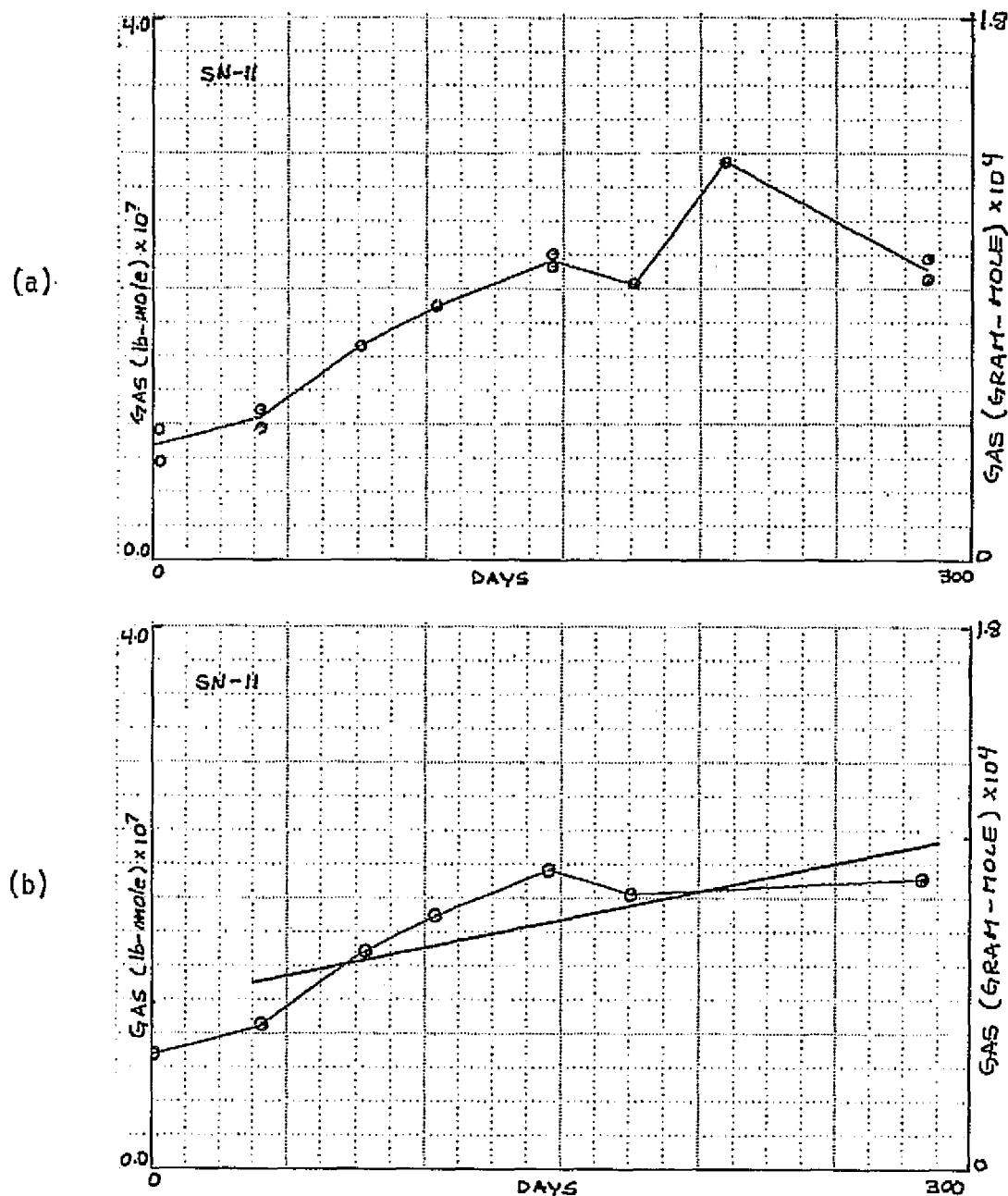


Figure 4-16. Gas Generation Data for Heat Pipe SN-11. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

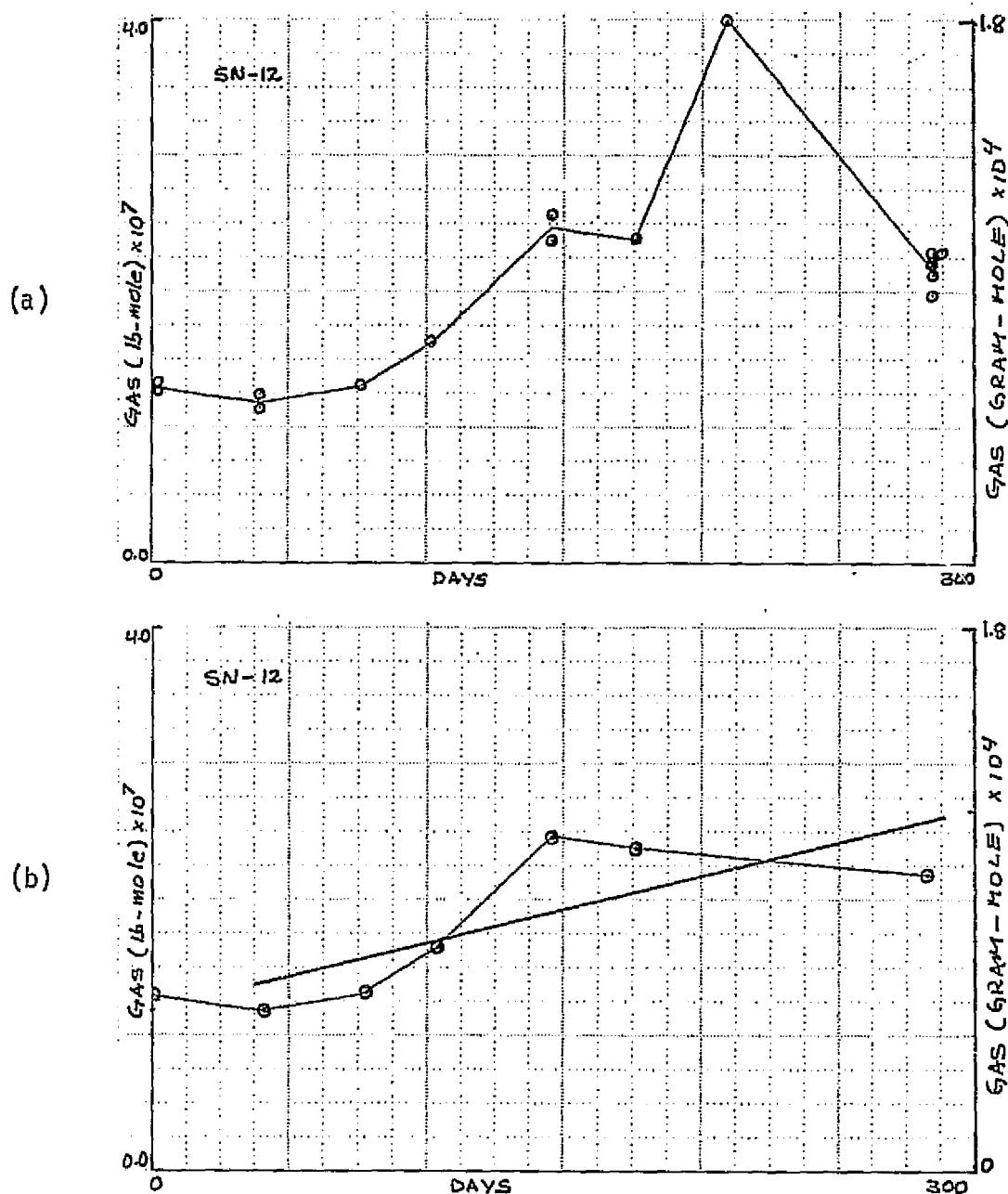


Figure 4-17. Gas Generation Data for Heat Pipe SN-12. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

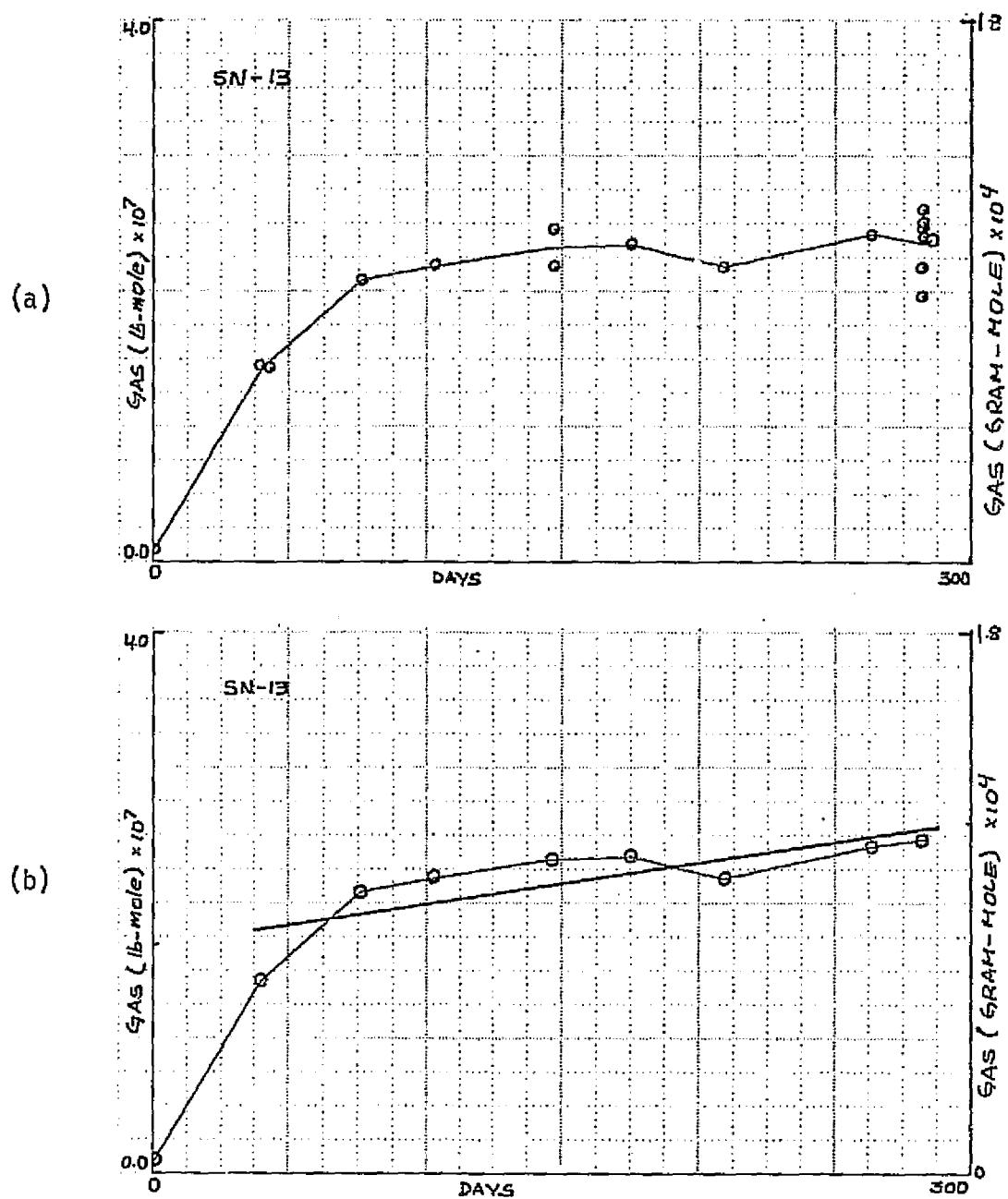


Figure 4-18. Gas Generation Data for Heat Pipe SN-13. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

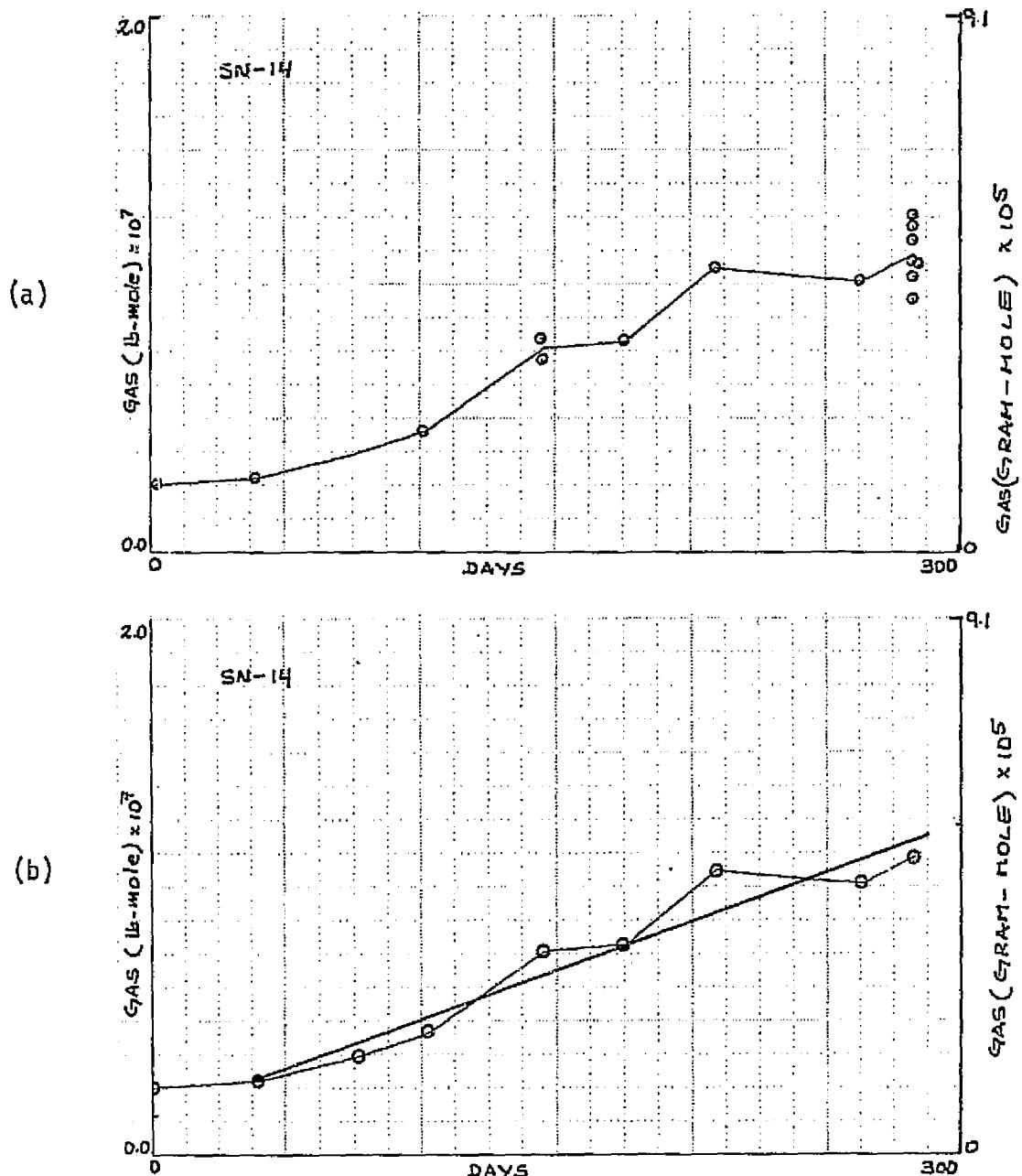


Figure 4-19. Gas Generation Data for Heat Pipe SN-14. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

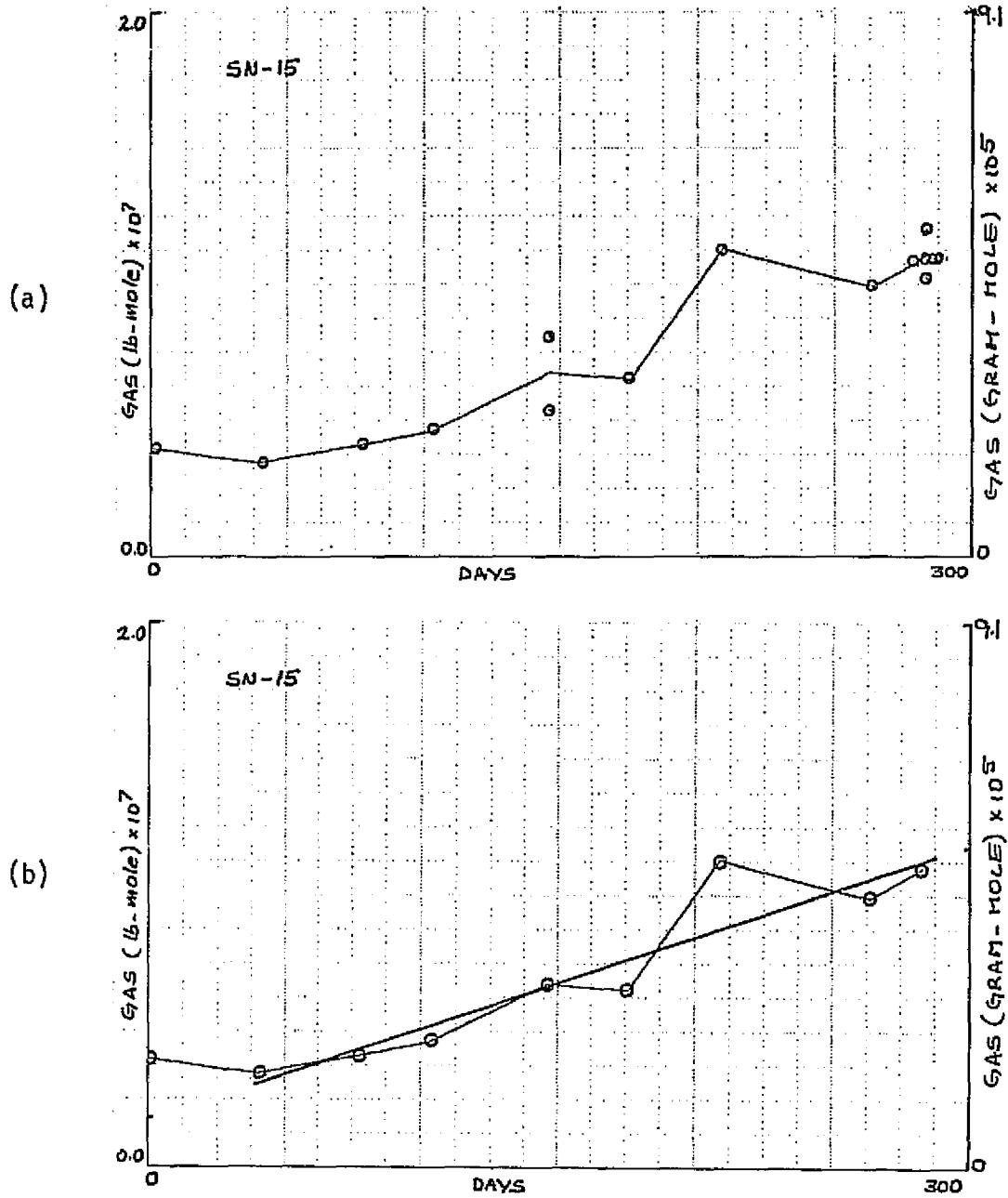


Figure 4-20. Gas Generation Data for Heat Pipe SN-15. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

ORIGINAL PAGE IS
OF POOR QUALITY

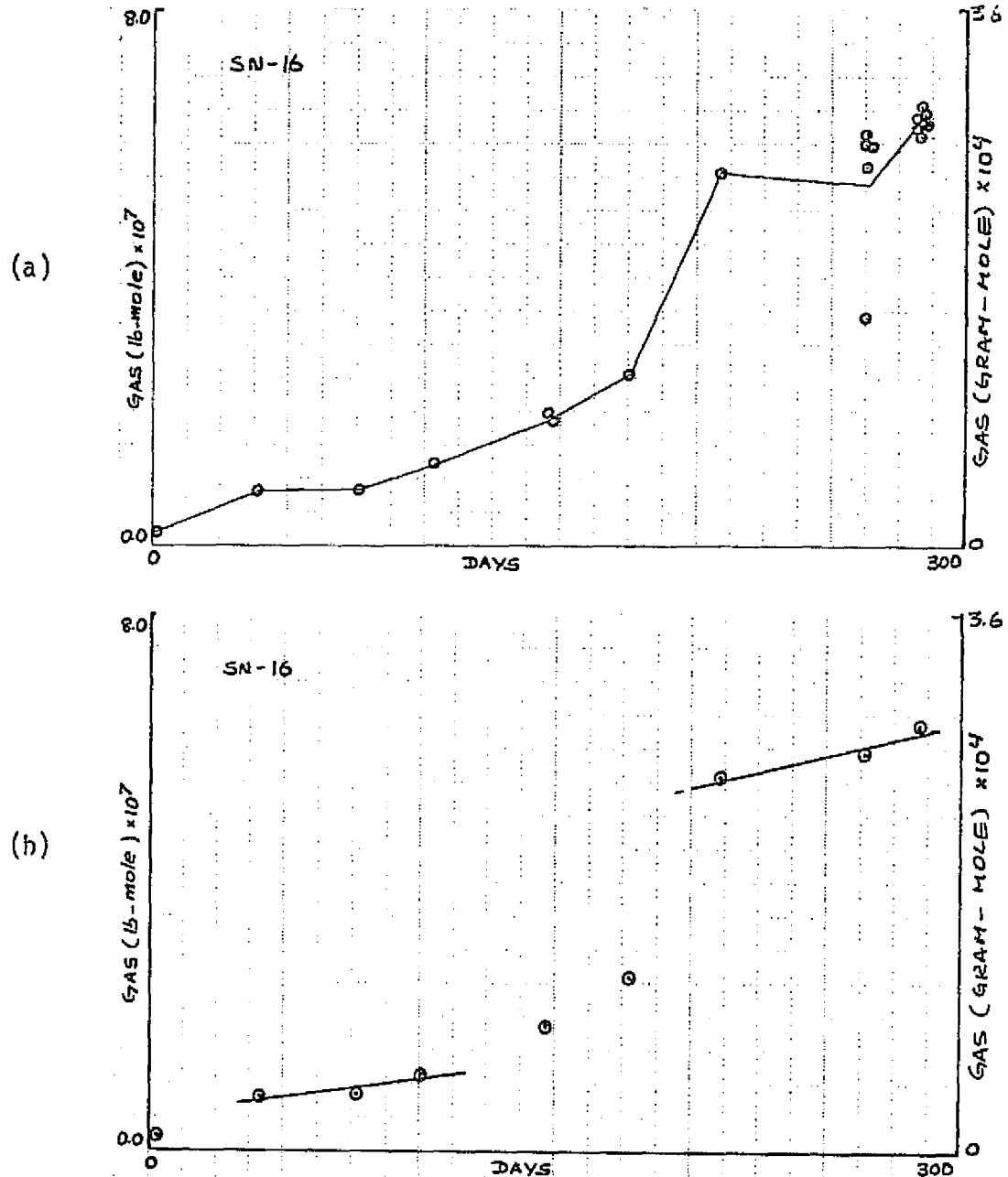


Figure 4-21. Gas Generation Data for Heat Pipe SN-16. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

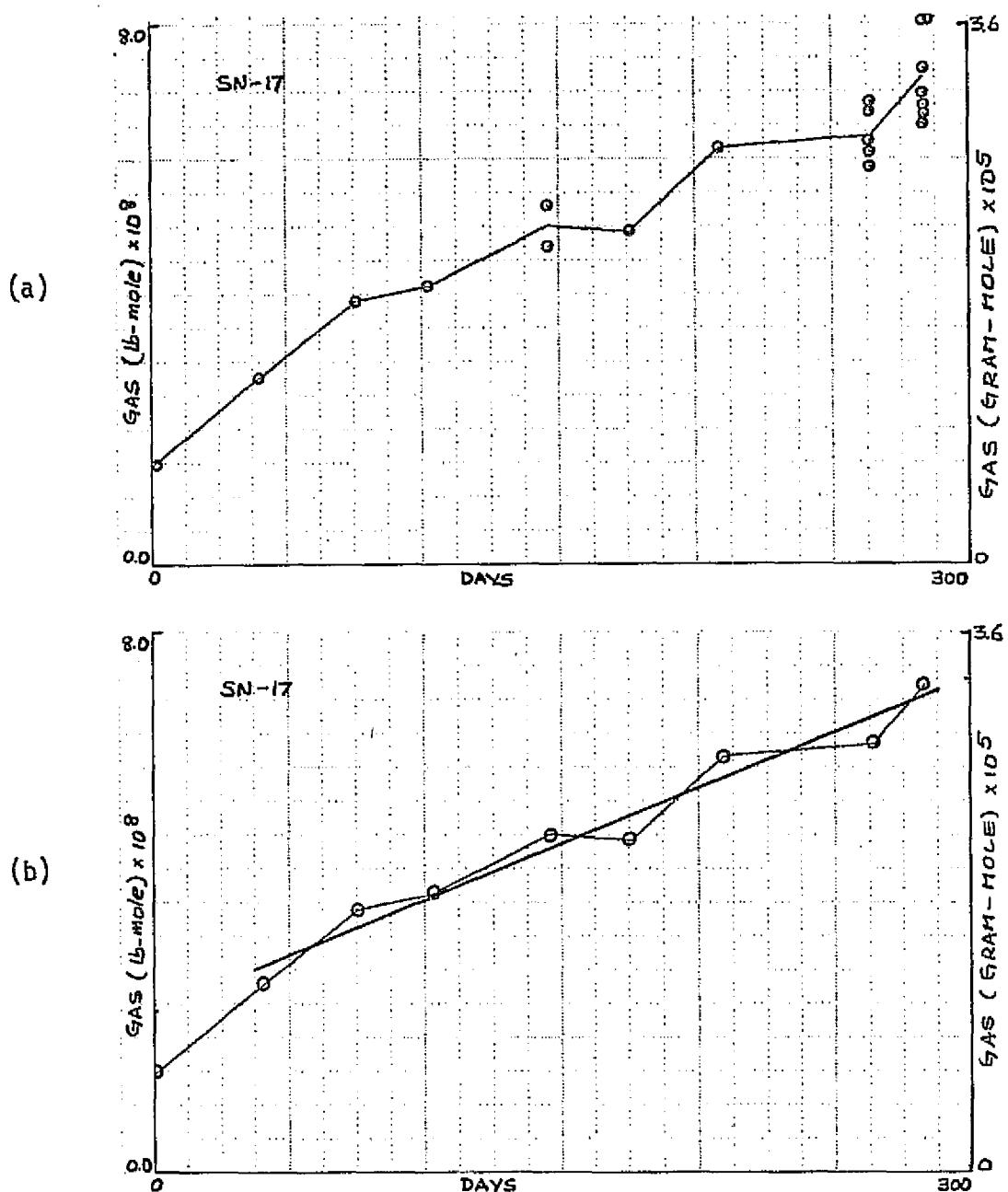


Figure 4-22. Gas Generation Data for Heat Pipe SN-17. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

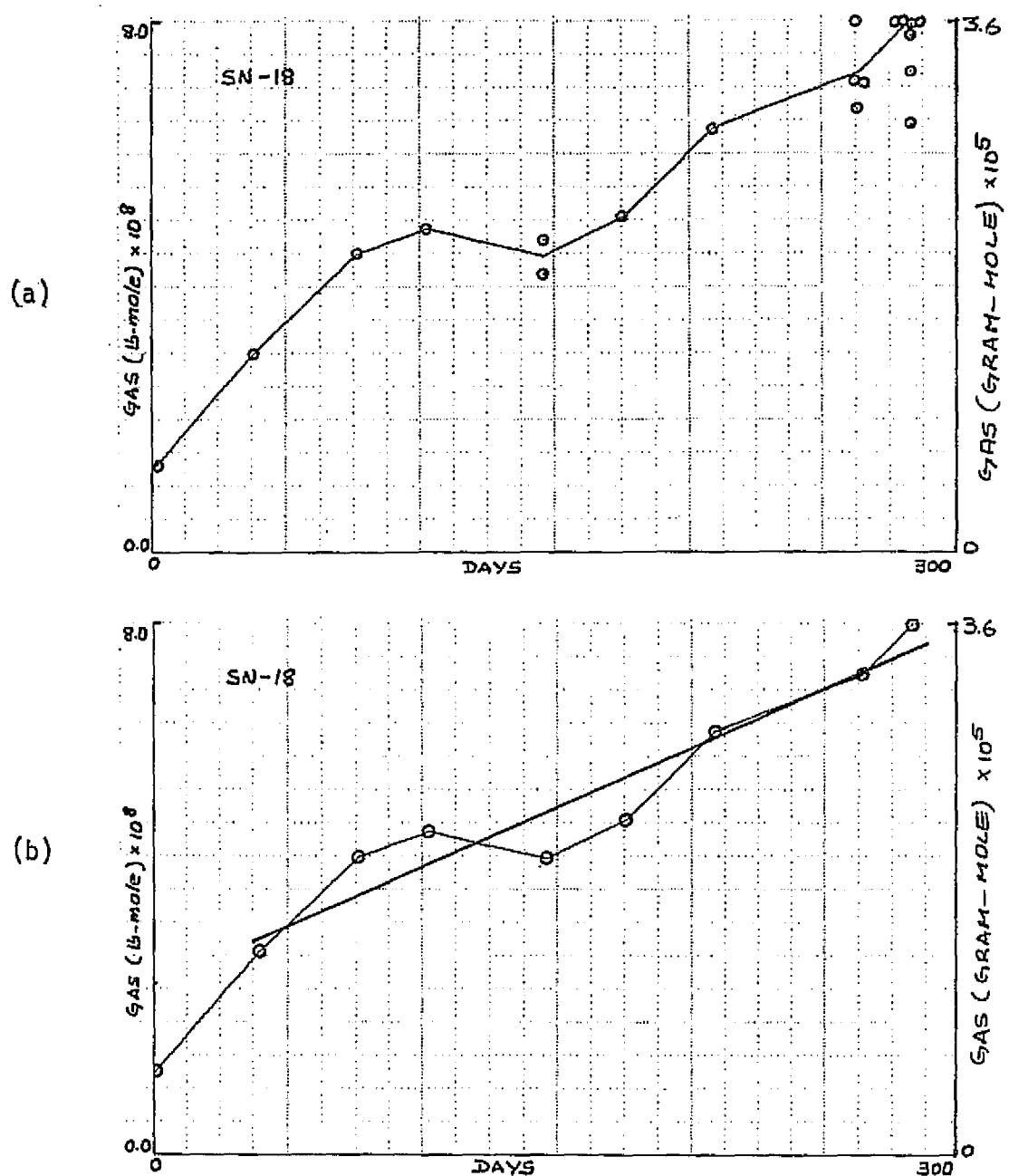


Figure 4-23. Gas Generation Data for Heat Pipe SN-18. Upper (a) curve shows all data, lower (b) curve is screened and curve fit deleting the initial measurement.

As seen in Figures 4-7 through 4-23, the largest number of data for each heat pipe were taken at the end of the life test period, the motivation being to improve the statistics and, thus, to establish with a higher degree of certainty the final gas inventories. This being also indispensable to make a fair screening of all the data throughout the duration of the life tests.

The resulting screening and subsequent averaging of the gas inventories is shown in Table 4-4. These data are plotted as a function of days of test duration in Figures 4-7b through 4-23b. As seen in the figures, the data screening results, in general, in a significant reduction of data scattering. Also shown in these figures is the least squares fit of the data with a polynomial of first order. Except for SN 16, the polynomial represent the best fit of the data from day 40 to day 283, the end of the test period.

Referring to Figures 4-21b, it can be seen that the gas evaluation in SN 16 experiences a sharp change between days 103 and 209. In the first part of the test period, the gas inventory of this heat pipe establishes a linear trend after day 40 which continues until day 103. Thereafter, the gas evolution becomes nonlinear and increases rapidly until day 209 beyond which the temporal gas inventory adopts again a linear mode of change. Thus, it becomes appropriate to fit the gas inventories with two first degree polynomials, one reflecting the gas generation in the first part of the test period and another at the end of the test.

The sharp discontinuity in the gas inventory can be speculated to be the result of cracking of the oxide film on the passivated surface, due to perhaps thermal stresses, which exposes the fluid to alloying impurities such as described in Section 3.0. An abnormal amount of gas is therefore generated until the site is depleted of impurities due to the chemical reaction and/or the oxide film is re-established. It can also be surmised that chemical

Table 4-4
SCREENED QUANTITY OF GAS GENERATED THROUGHOUT THE TEST

Heat Pipe Serial Number	DAYS FROM INITIAL GAS MEASUREMENTS (LB-MOLE)								
	0	40	76	103	146	176	209	264	283
1	1.67 E-7	2.14 E-7	3.30 E-7	3.35 E-7	3.62 E-7	3.76 E-7	4.14 E-7	4.27 E-7	4.41 E-7
2	1.0 E-7	1.62 E-7	2.62 E-7	3.07 E-7	3.22 E-7	3.44 E-7	3.63 E-7	3.53 E-7	3.59 E-7
3	3.11 E-7	4.82 E-7	6.69 E-7	7.08 E-7	7.28 E-7	-	7.46 E-7	7.80 E-7	7.75 E-7
4	3.95 E-7	7.28 E-7	8.79 E-7	8.68 E-7	9.01 E-7	8.74 E-7	9.18 E-7	8.55 E-7	9.53 E-7
5	2.65 E-7	3.20 E-7	3.78 E-7	4.31 E-7	-	4.53 E-7	4.23 E-7	4.42 E-7	4.32 E-7
6	6.66 E-6	-	-	-	-	-	-	-	-
7	3.89 E-7	4.32 E-7	3.68 E-7	4.85 E-7	5.15 E-7	4.32 E-7	4.88 E-7	4.8 E-7	5.32 E-7
8	7.10 E-7	7.16 E-7	7.87 E-7	8.55 E-7	8.92 E-7	1.0 E-6	1.03 E-6	1.17 E-6	1.16 E-6
9	4.25 E-7	4.48 E-7	4.70 E-7	4.89 E-7	5.46 E-7	5.0 E-7	-	-	6.08 E-7
10	1.17 E-7	1.31 E-7	1.31 E-7	1.62 E-7	2.19 E-7	2.36 E-7	-	-	1.90 E-7
11	8.42 E-8	1.05 E-7	1.58 E-7	1.86 E-7	2.21 E-7	2.03 E-7	-	-	2.14 E-7
12	1.29 E-7	1.18 E-7	1.30 E-7	1.04 E-7	2.46 E-7	2.38 E-7	-	-	2.18 E-7
13	7.70 E-9	1.42 E-7	2.08 E-7	2.18 E-7	2.32 E-7	2.34 E-7	2.18 E-7	2.42 E-7	2.47 E-7
14	2.50 E-8	2.74 E-8	3.66 E-8	4.55 E-8	7.60 E-8	7.85 E-8	1.05 E-7	1.01 E-7	1.11 E-7
15	3.98 E-8	4.07 E-8	4.60 E-8	6.74 E-8	6.52 E-8	6.52 E-8	1.13 E-7	9.90 E-8	1.10 E-7
16	1.78 E-8	8.22 E-8	8.36 E-8	1.97 E-7	1.87 E-7	2.57 E-7	5.57 E-7	5.89 E-7	6.35 E-7
17	1.45 E-8	2.76 E-8	3.90 E-8	4.12 E-8	5.01 E-8	4.92 E-8	6.16 E-8	6.34 E-8	7.21 E-8
18	1.22 E-8	3.06 E-8	4.48 E-8	4.87 E-8	4.46 E-8	5.05 E-8	6.38 E-8	7.22 E-8	8.01 E-8

etching of sections of the weld could have reached a site of trapped gas stemming from the weld operation. This seems unlikely since estimates of possible entrapment of gas in the weld can not account for such a substantial increase in the gas inventory as seen in Figure 4-21a or 4-21b.

The average gas generation rates, as given by the slopes of the least squares polynomials, and the gas inventories based on the average of the screened data are shown in Table 4-5.

4.5.2 Group Test Results

In order to compare the materials compatibility performance of heat pipes belonging to a given case group, plots are summarized in 4-24-a-b-c through 4-29-a-b-c. Figures 4-24a through 4-29a show the average gas inventories based on raw data.

Temporal gas inventories based on averaged screened data are shown in Figures 4-24-b through 4-29-b. Also shown in these figures are the least square fit of the data with first order polynomials.

It can be seen in every group, except the one corresponding to the set with chemically cleaned/ammonia refluxed heat pipes, that two heat pipes out of three yield very similar performance which is generally substantially different from that of the third heat pipe. This observation raises the same issue discussed in the coupon section which involves the fact that processing of heat pipes is statistical in nature. As a result, heat pipes fabricated and processed following the same identical procedures will not necessarily assure identical performance, particularly in terms of their materials compatibility.

Owing to the fact that in general the performance of one heat pipe of a group departs measurably from that of the other two heat pipes, the goal of representing the performance of a case group

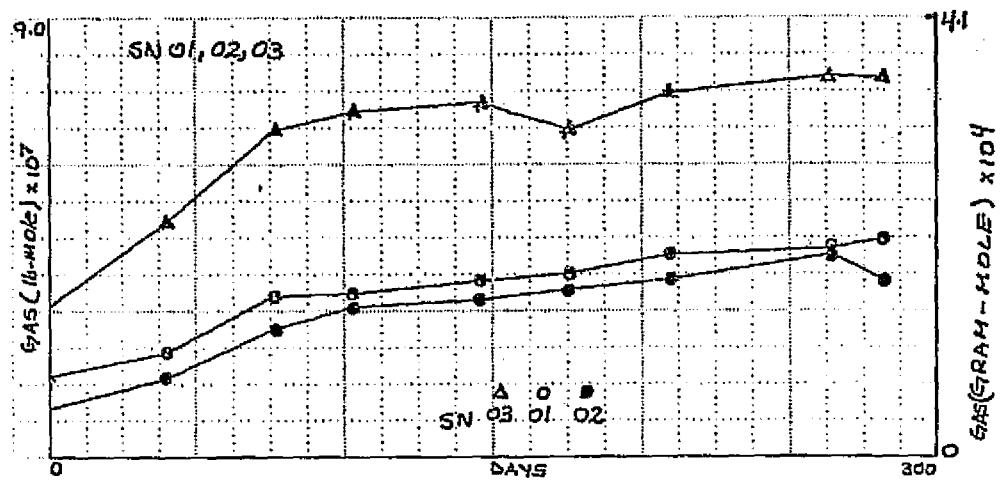
Table 4-5

VALUES FOR GAS - GENERATION RATES AND
QUANTITY OF GAS GENERATED AT END OF TEST

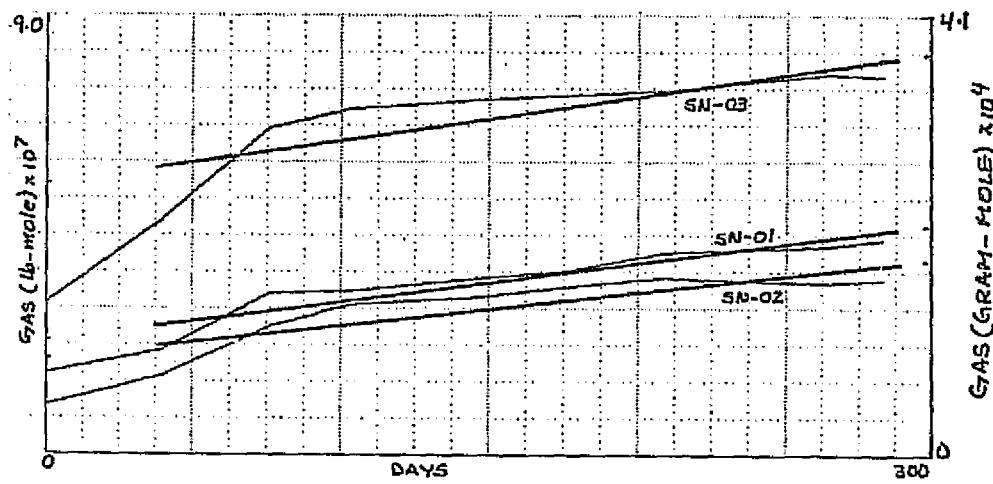
Heat Pipe Serial Number	Reflux Procedure			Cleaning Procedure	Test Temperature °C	Average Generation Rate (LB - Mole/Day)	Gas At End Of Test (283 Days) (LB-Mole)
	% H ₂ O	Temp °C	Time Hrs.				
1	0.0	80	16	Solvent Per PR2-28-1	80	7.71×10^{-10}	4.41×10^{-7}
2						6.63×10^{-10}	3.59×10^{-7}
3						8.96×10^{-10}	7.75×10^{-7}
4	3.0					5.05×10^{-10}	9.53×10^{-7}
5						3.69×10^{-10}	4.32×10^{-7}
7						3.86×10^{-10}	5.32×10^{-7}
8	10.0					1.89×10^{-9}	1.16×10^{-6}
9						6.29×10^{-10}	6.08×10^{-7}
10						3.32×10^{-10}	1.90×10^{-7}
11	0.0			Chemical Per CRP7-10		3.93×10^{-10}	2.14×10^{-7}
12						4.84×10^{-10}	2.18×10^{-7}
13						3.00×10^{-10}	2.47×10^{-7}
14	3.0					3.62×10^{-10}	1.11×10^{-7}
15						3.37×10^{-10}	1.10×10^{-7}
16						$5.54 \times 10^{-10} (*)$	6.35×10^{-7}
17	10.0					$9.48 \times 10^{-10} (**)$	6.35×10^{-7}
18						1.64×10^{-10}	7.21×10^{-8}
						1.71×10^{-10}	8.01×10^{-8}

(*) Initial Generation Rate

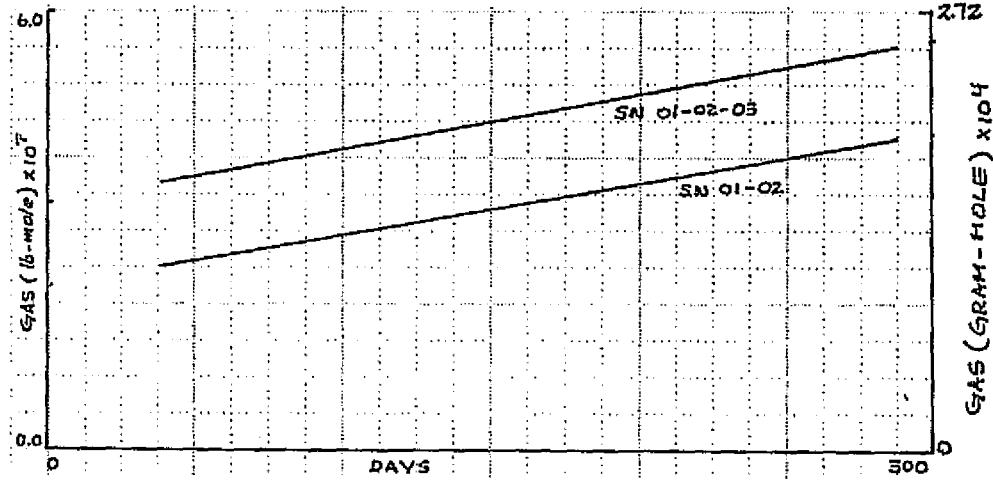
(**) Generation Rate At End Of Test



(a) Based on Raw Data



(b) Based on Screen Data



(c) Least Squares Fit Based on (b) Data

Figure 4-24. Gas Generation Data for Solvent Cleaned, Pure NH_3 Refluxed Heat Pipes

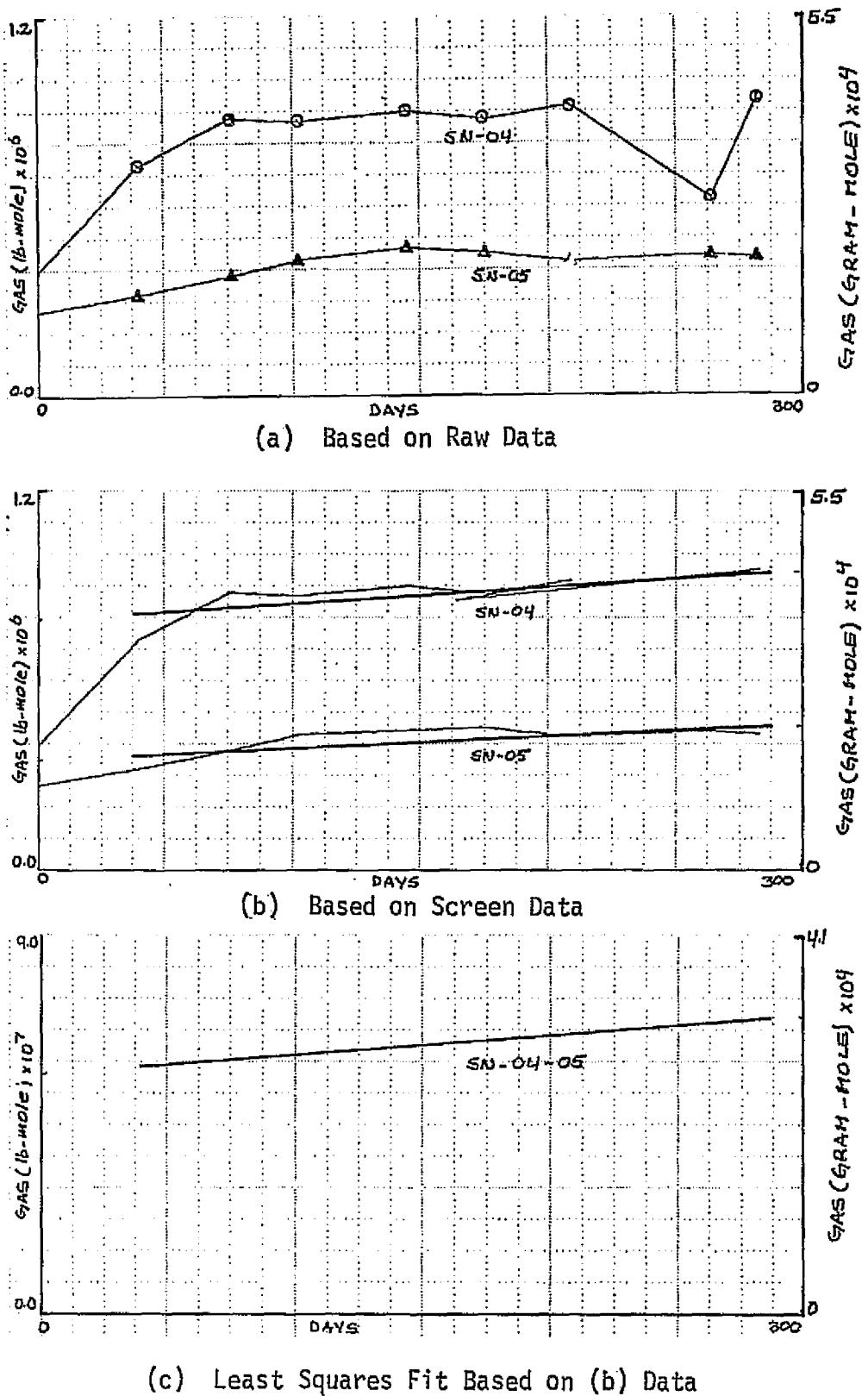
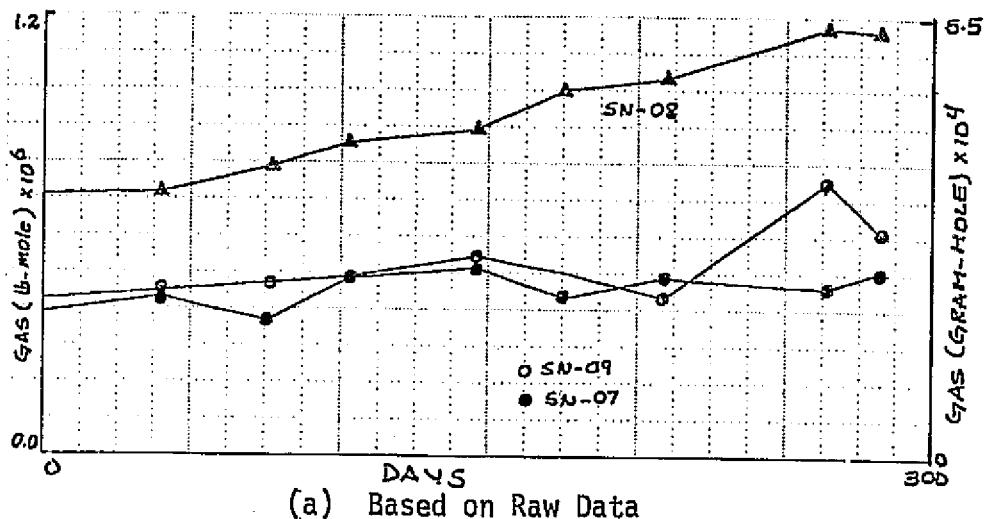
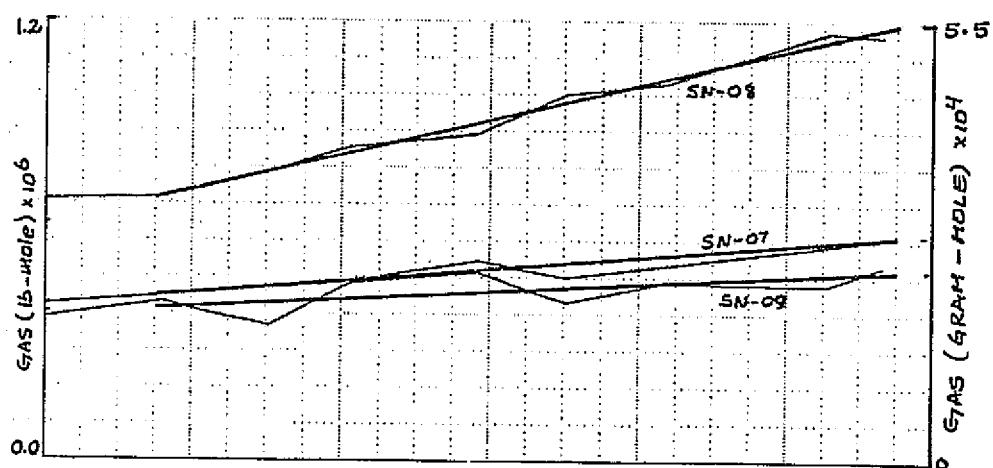


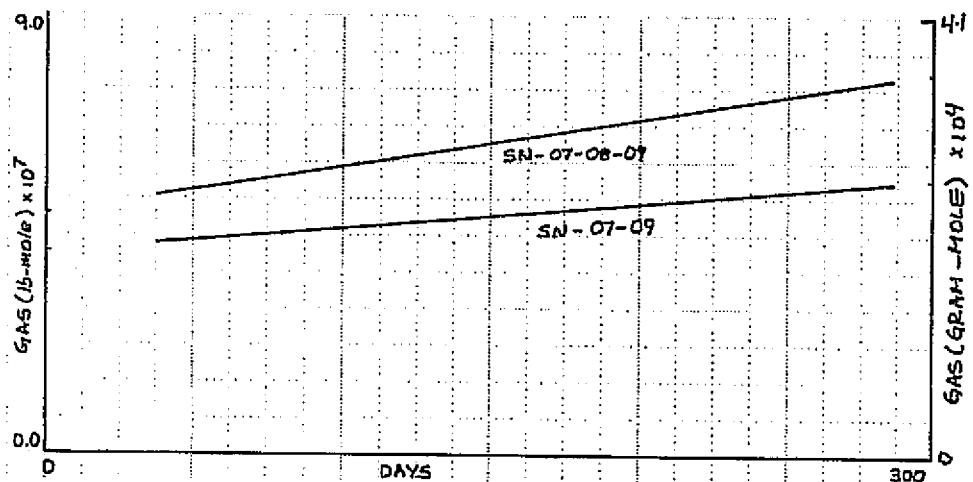
Figure 4-25. Gas Generation Data for Solvent Cleaned, 3% H₂O/
97% NH₃ Refluxed Heat Pipes



(a) Based on Raw Data

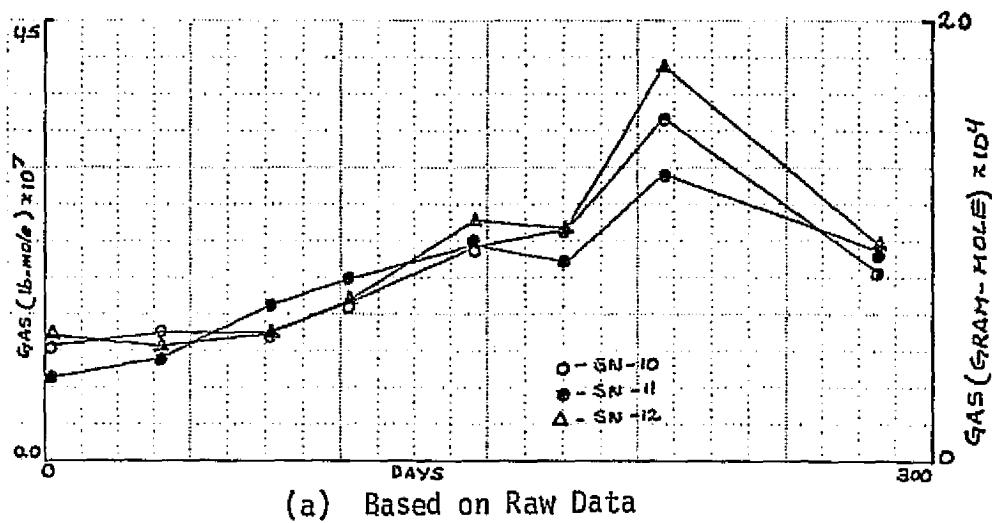


(b) Based on Screen Data

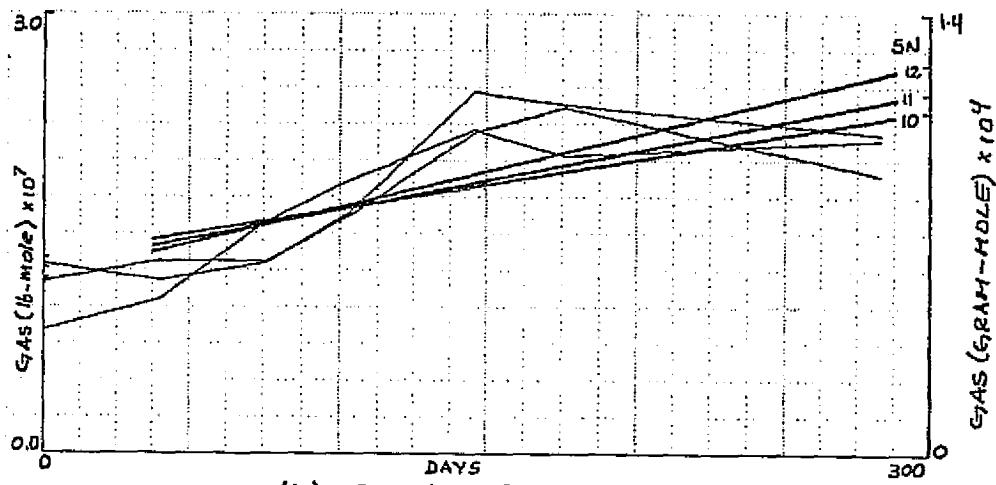


(c) Least Squares Fit Based on (b) Data

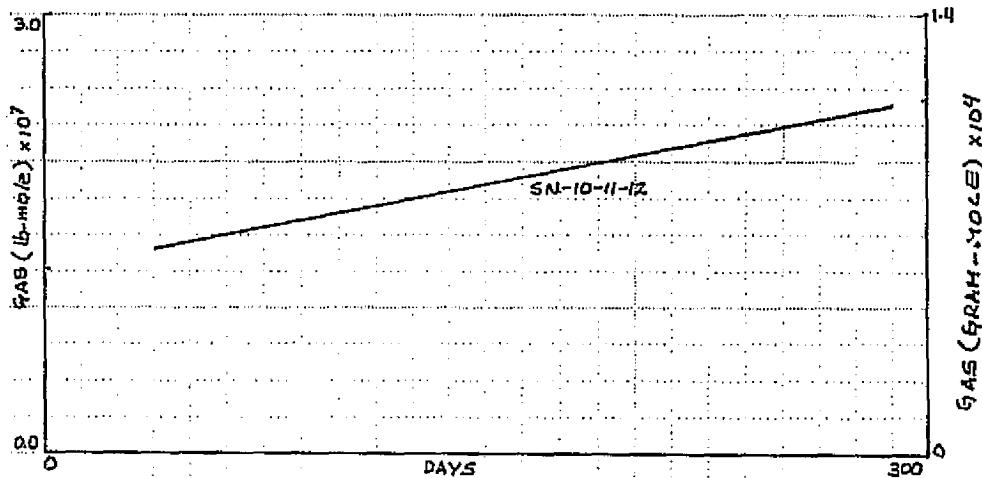
Figure 4-26. Gas Generation Data for Solvent Cleaned, 10% H₂O/90% NH₃ Refluxed Heat Pipes



(a) Based on Raw Data

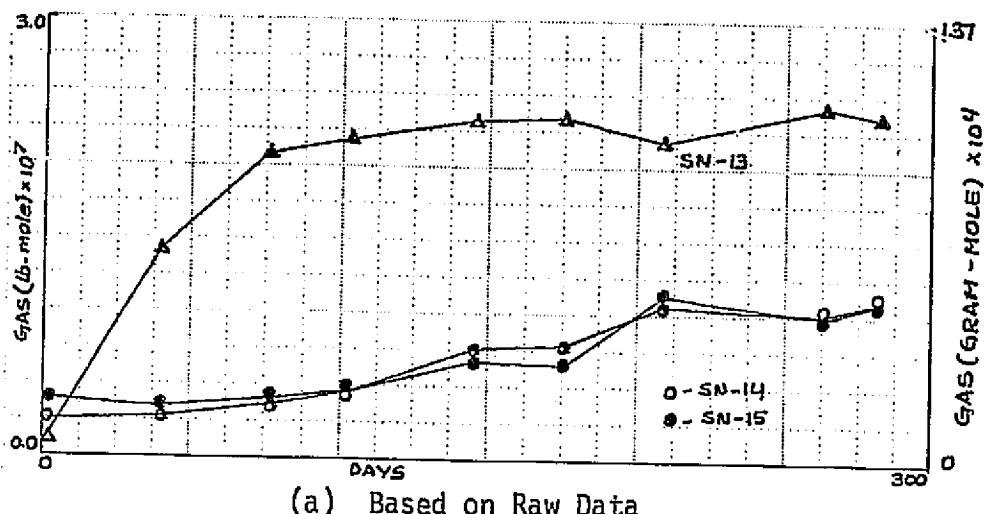


(b) Based on Screen Data

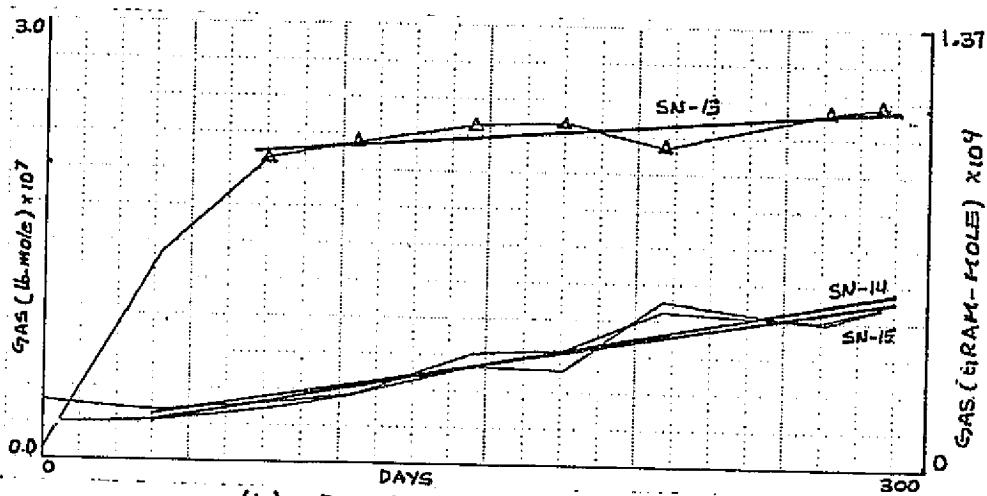


(c) Least Squares Fit Based on (b) Data

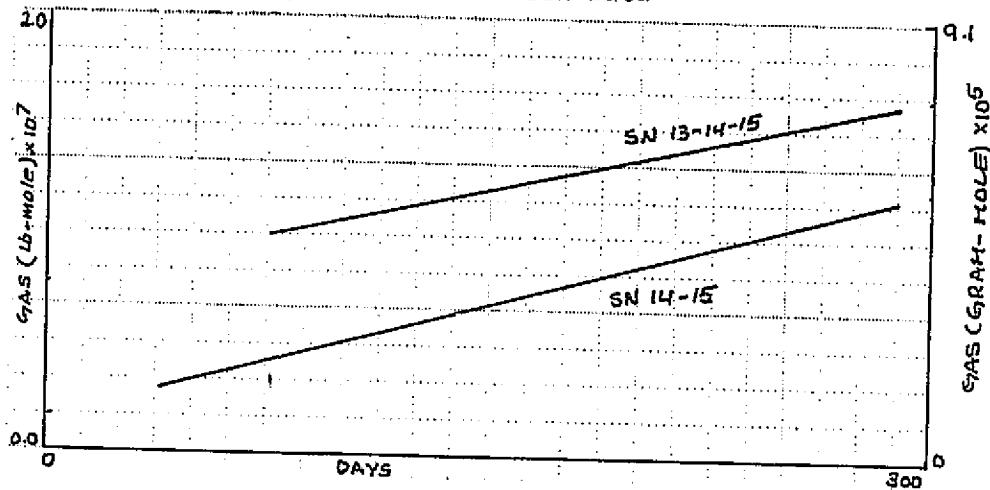
Figure 4-27. Gas Generation Data for Chemically Cleaned, Pure NH_3 Refluxed Heat Pipes



(a) Based on Raw Data



(b) Based on Screen Data



(c) Least Squares Fit Based on (b) Data

Figure 4-28. Gas Generation Data for Chemically Cleaned, 3% H₂O/97% NH₃ Refluxed Heat Pipes

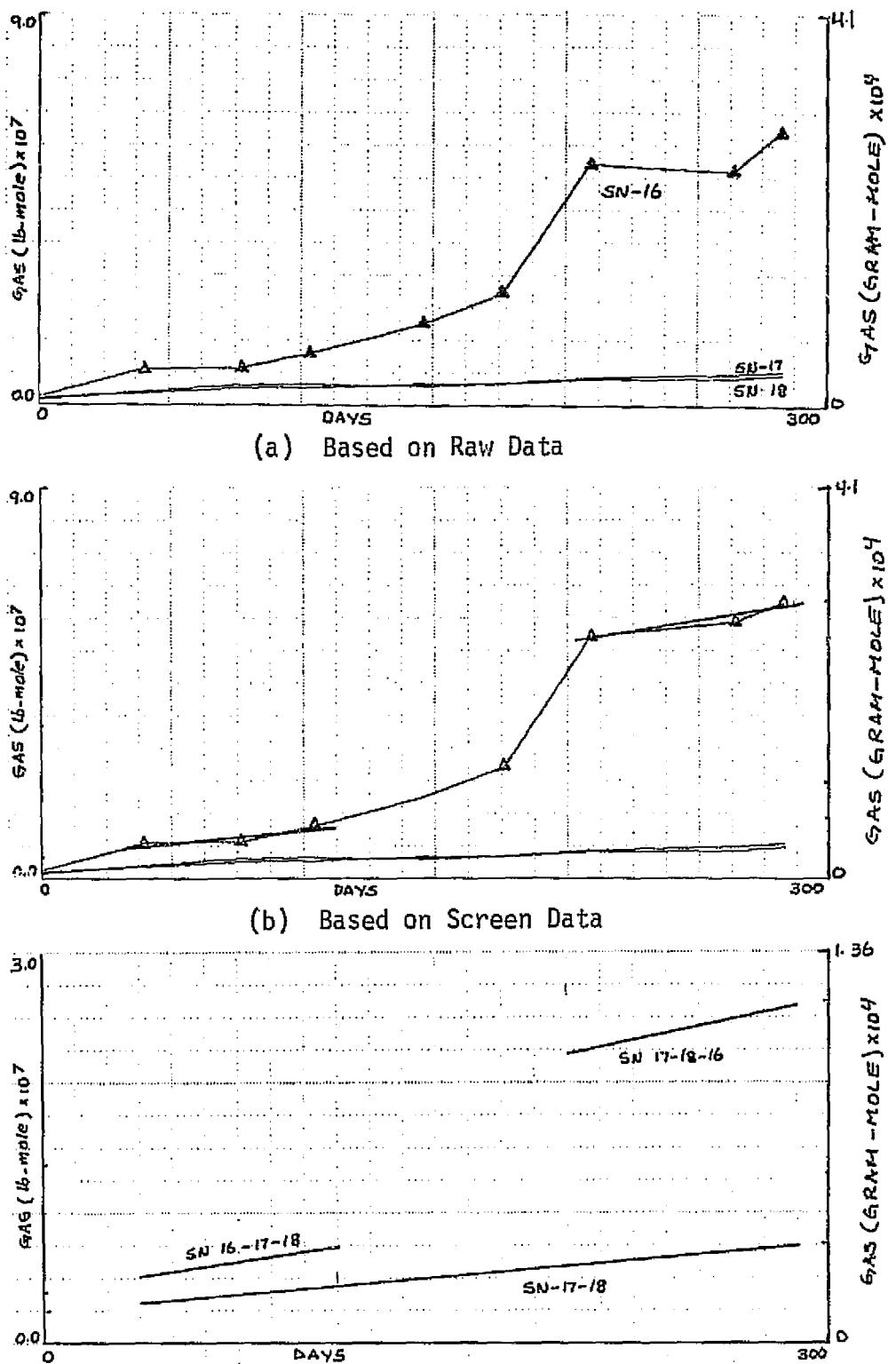


Figure 4-29. Gas Generation Data for Chemically Cleaned, 10% H₂O/90% NH₃ Refluxed Heat Pipes

with a single temporal gas inventory curve can not be fairly realized with the exception of the chemically cleaned/0% H₂O-100% ammonia group. As a result, Figures 4-24-c through 4-29-c, except 4-25-c and 4-27-c, show more than one curve.

Analyzing the data in these figures, it can be readily seen that one curve represents statistically the best performance and the other represents the overall or average performance of the group.

Inclusion of a best curve is found necessary in order to meet the main objective of this program which is to determine the effects of the cleaning procedures, chemical and solvent, and the presence of water in the refluxing stage on the performance of aluminum/ammonia heat pipes. The overall or average performance curve of a group can be found useful for thermal design purposes. The gas generation rates, given by the slopes of these curves, and the averaged best and overall gas inventories of each group at the end of the life tests are tabulated in Table 4-5.

Figure 4-30(a) shows the best and overall curves for the solvent cleaned groups. Since the average fit of SN 01-02, SN 04-05, and SN 07-09 are considered representatives of the 0% H₂O/100% NH₃, 3% H₂O/97% NH₃, and 10% H₂O/90% NH₃ groups respectively, it can be seen that there appears to be little correlation between the amount of water in the refluxing charge and the total gas generated among the solvent cleaned heat pipes. However, referring to Table 4-5 or Figure 4-31 it can be seen that the representative gas generation rates for the heat pipe groups refluxed with 3% and 10% water, are 40% and 30% lower than the group refluxed without water. The fact that the performance of the 3% H₂O group is based on the performance of the two remaining heat pipes, whereas the performance of the 10% H₂O group was selected from that of three heat pipes, a fair comparison between the two groups can not be made.

Table 4-5

AVERAGE VALUES FOR GAS GENERATION RATES AND
QUANTITY OF GAS GENERATED AT END OF TEST FOR EACH HEAT PIPE GROUP

Heat Pipe Serial Number	Reflux Procedure			Cleaning Procedure	Test Temperature °C	Average Generation Rate (LB - Mole/Day)	Gas At End Of Test (283 Days) (LB-Mole)
	% H_2O	Temp °C	Time Hrs.				
SN 01,02,03	0%	80	16	Solvent Per PR 2-28-1	80°C		
(01+02+03)/3						7.78×10^{-10}	5.25×10^{-7}
(01+02)/2						7.19×10^{-10}	4.00×10^{-7}
SN 04,05	3%						
(04+05)/2						4.36×10^{-10}	6.93×10^{-7}
SN 07,08,09	10%						
(07+08+09)/3						9.65×10^{-10}	7.67×10^{-7}
(07+09)/2						5.05×10^{-10}	5.70×10^{-7}
SN10,11,12	0%			Chemical Per CRP 7-10			
(10+11+12)/3						4.03×10^{-10}	2.07×10^{-7}

SN13,14,15	3%						
(13+14+15)/3						2.94×10^{-10}	1.56×10^{-7}
(14+15)/2						3.50×10^{-10}	1.11×10^{-7}
SN16,17,18	10%						
(16+17+18)/3						(*) 3.16×10^{-10}	2.62×10^{-7}
(16+17+18)/3						(**) 4.18×10^{-10}	2.62×10^{-7}
(17+18)/2						1.71×10^{-10}	7.61×10^{-8}

(*) Gas Generation Rate From Days 40 To 103

(**) Gas Generation Rate From Days 209 To 283

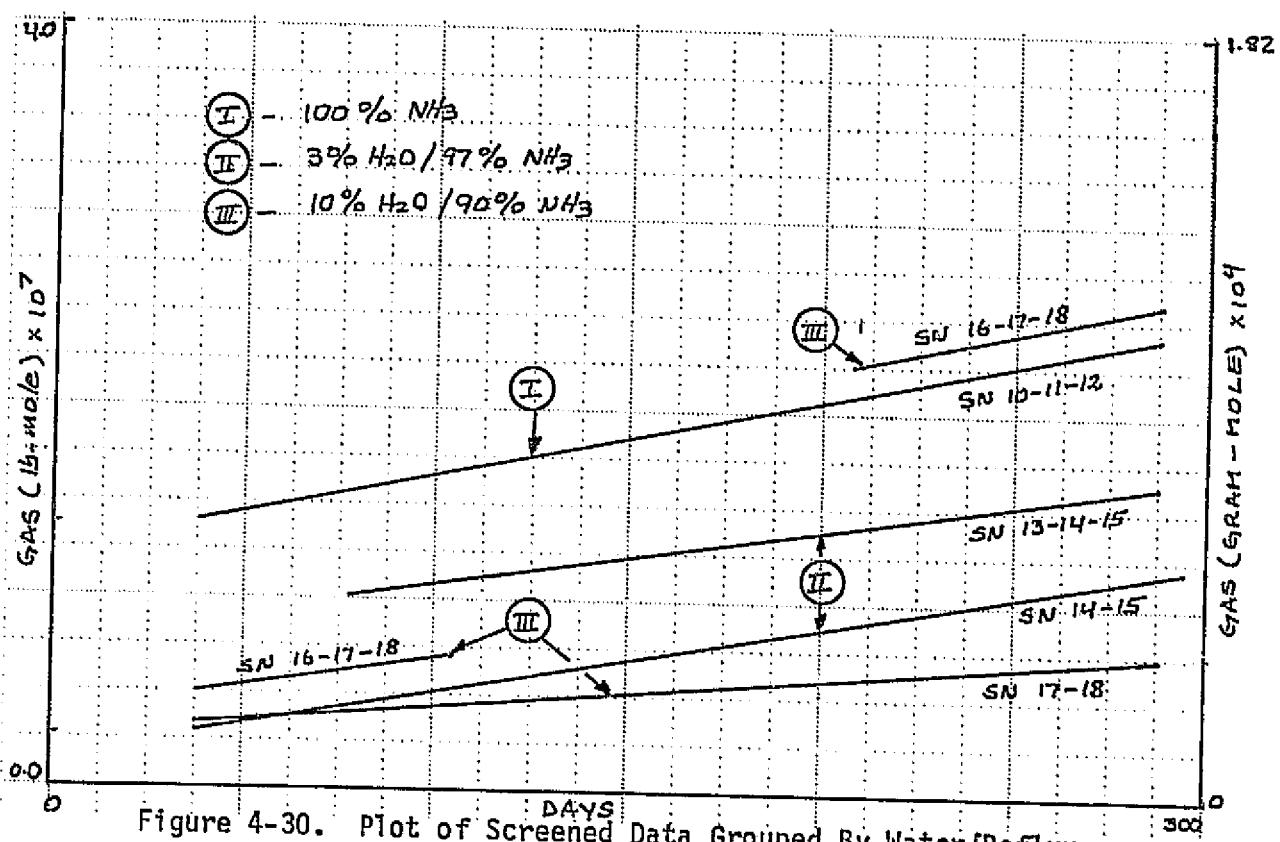
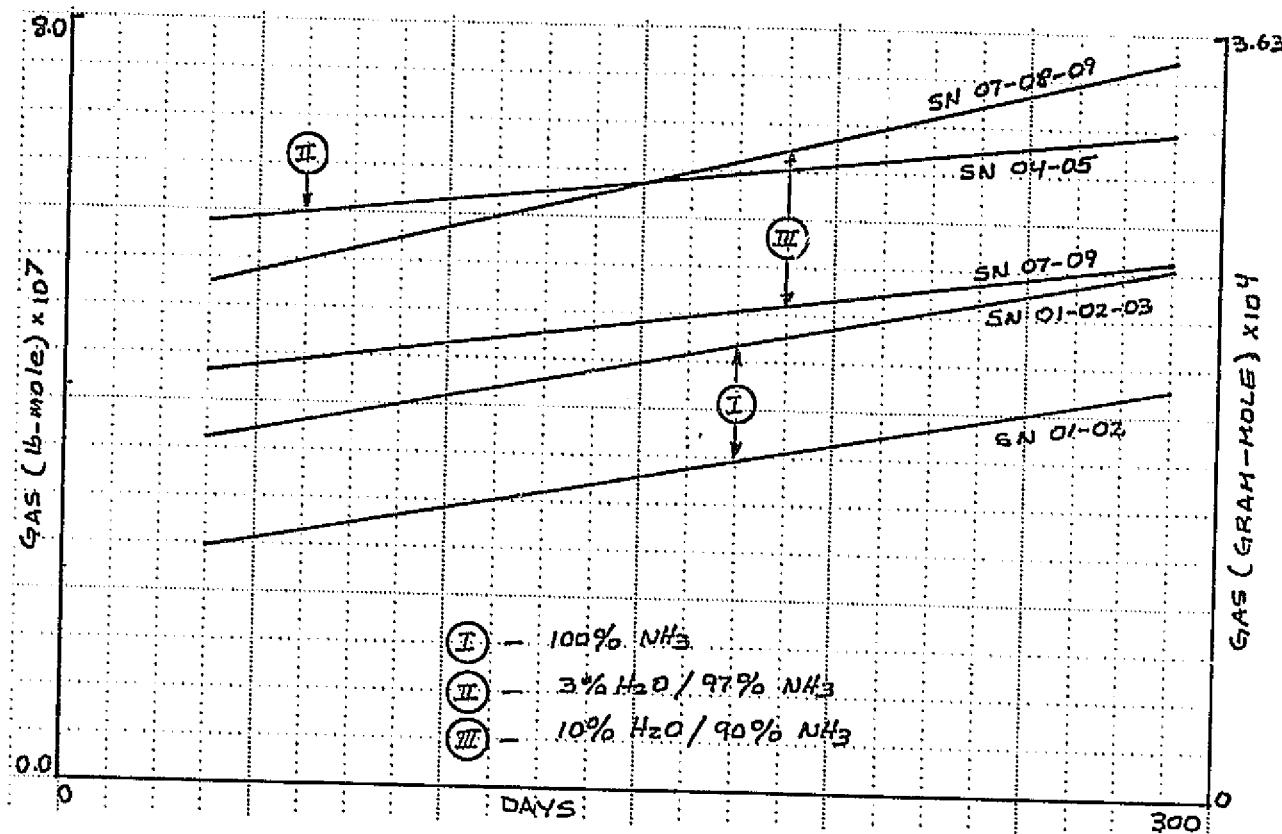


Figure 4-30. Plot of Screened Data Grouped By Water/Reflux Content. Upper Curve (a) Solvent Cleaned Heat Pipes, Lower Curve (b) Chemically Cleaned Heat Pipes

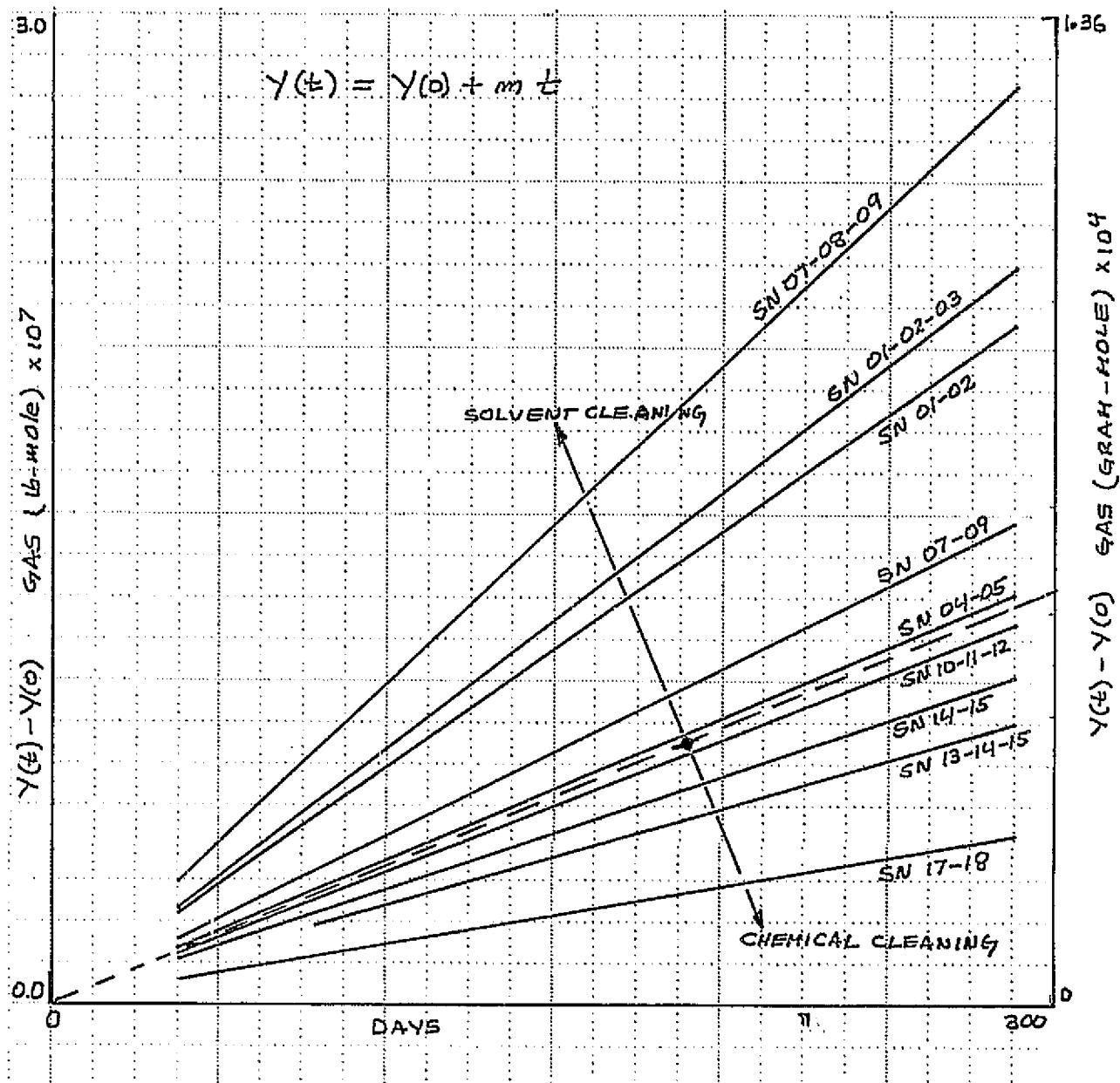


Figure 4-31. Gas Generation Rates (m) (After Initial Measurement) For All Heat Pipes

The analysis of the solvent cleaned group indicates that the heat pipes refluxed with water generate initially more gas than the heat pipes refluxed with no water, however their gas inventories level out more rapidly as reflected by their lower gas generation rates at the end of the test. The performance of the chemically cleaned heat pipe groups is summarized in Figure 4-30(b).

Owing to the anomalous behavior of SN 16 which can not be attributed to the cleaning nor the refluxing process to which it was subjected, the average best fit curve for SN 17-18 most accurately represents the performance of the 10% H₂O group. The two additional curves for this group, SN 16-17-18, are presented merely for completion of the data.

The results indicate that in terms of gas generation rate and gas inventories, particularly after day 62, there is a distinct and positive correlation between performance and the amount of water present during refluxing stages of heat pipe processing.

4.5.3 Conclusion

In order to compare the performance of the chemically cleaned heat pipes to those solvent cleaned, it is convenient to make reference to Figures 4-31 and 4-32 which enable one to analyze the two major heat pipe sets in terms of their gas generation rates and their gas inventories' temporal behavior, respectively. The superiority of the chemical over the solvent cleaning procedure becomes apparent.

The results convincingly establish the fact that chemically cleaning the aluminum surface can have a beneficial effect in terms of improving the materials compatibility in aluminum/ammonia systems. In addition, the results indicate that such a beneficial effect can be enhanced by surface passivation derived from the presence of water during refluxing stages of heat pipe processing.

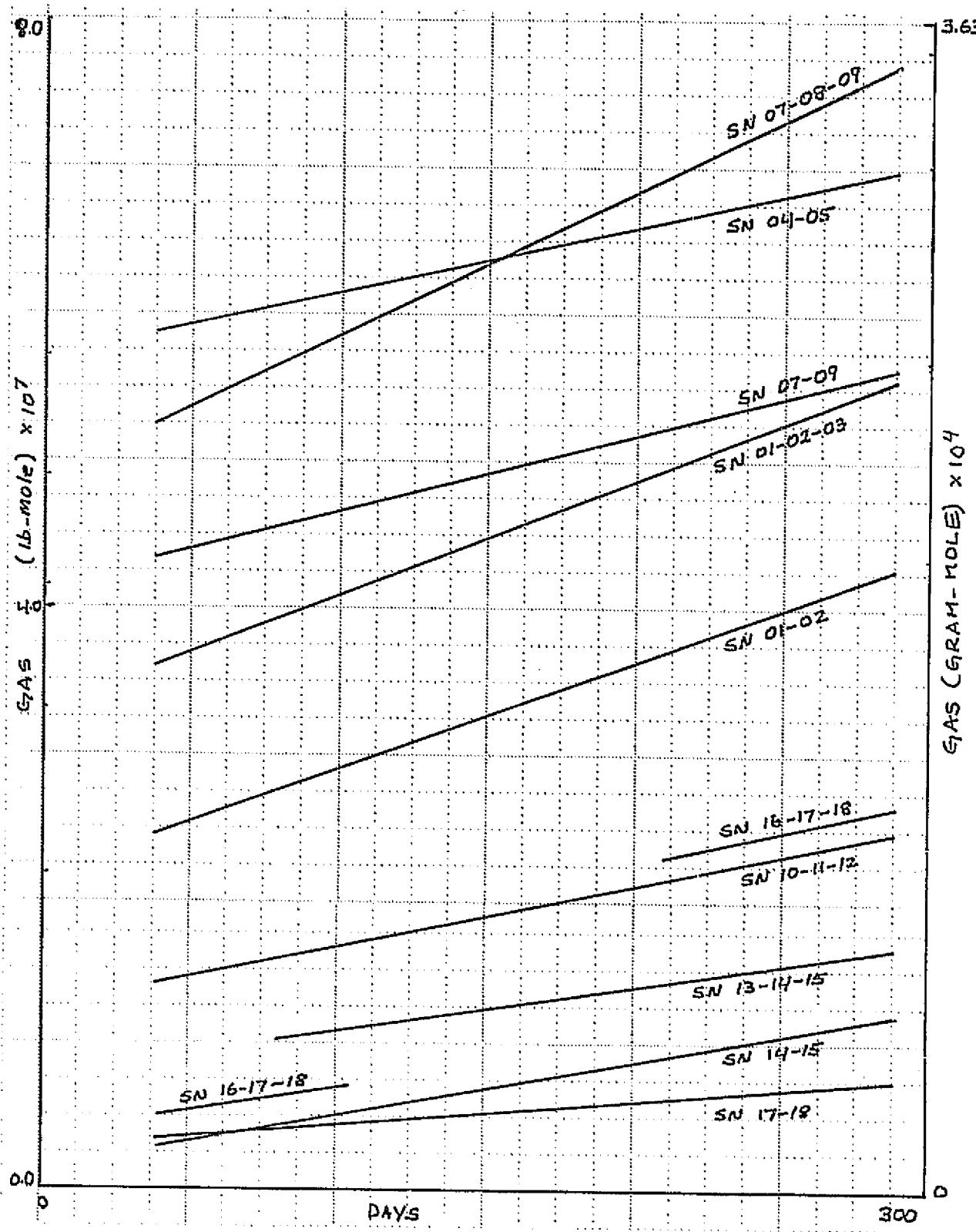


Figure 4-32. Total Gas Generated By All Heat Pipes

5.0 EFFECT OF GAS ON HEAT PIPE PERFORMANCE

The objective of this section is to demonstrate the effect of gas generation on the performance of two types of heat pipes in terms of the impact it has on the thermal control system into which the heat pipes are integrated. It should be noted that the data presented in this report was obtained for heat pipes operating at 80°C. Although it has been difficult to obtain consistent results for temperature/rate effects on gas generation in the current series of tests, Anderson et. al. ⁽²⁾ were able to demonstrate a well characterized temperature effect for methanol/nickel heat pipe systems. It is likely, therefore that actual spacecraft heat pipes operating at some nominal temperature between 20 and 50°C, and often lower, would generate considerably less gas than the values measured in this program.

5.1 Simple Heat Pipe Models

In order to assess the performance of a simple heat pipe as a function of gas inventory, the methodology of a TRW funded Independent Research and Development (IRAD) task was used. A thermal control system was assumed whose configuration is depicted in Figure 5-1. As shown, it consists of an aluminum radiator panel 8 inches wide, 40 inches long and 0.040 inches thick. It is assumed that power dissipating equipment is mounted over the first 12 inches of the panel. Dissipation of 100 watts is distributed uniformly over the width of the panel. The geometry assumes a 0.5 inch OD aluminum/stab wick/ammonia heat pipe, 40 inches long, is soldered to an aluminum extrusion saddle which has a 1.5 inch footprint. The heat pipe/saddle assembly is mounted on the back side along the entire length of the radiator panel. The top side of the panel radiates to a sink at -300°F. The nodalization of the lumped parameter model is shown in Figure 5.2.

(2) W. T. Anderson, "Hydrogen Evolution In Nickel-Water Heat Pipes", AIAA Paper No. 73-726

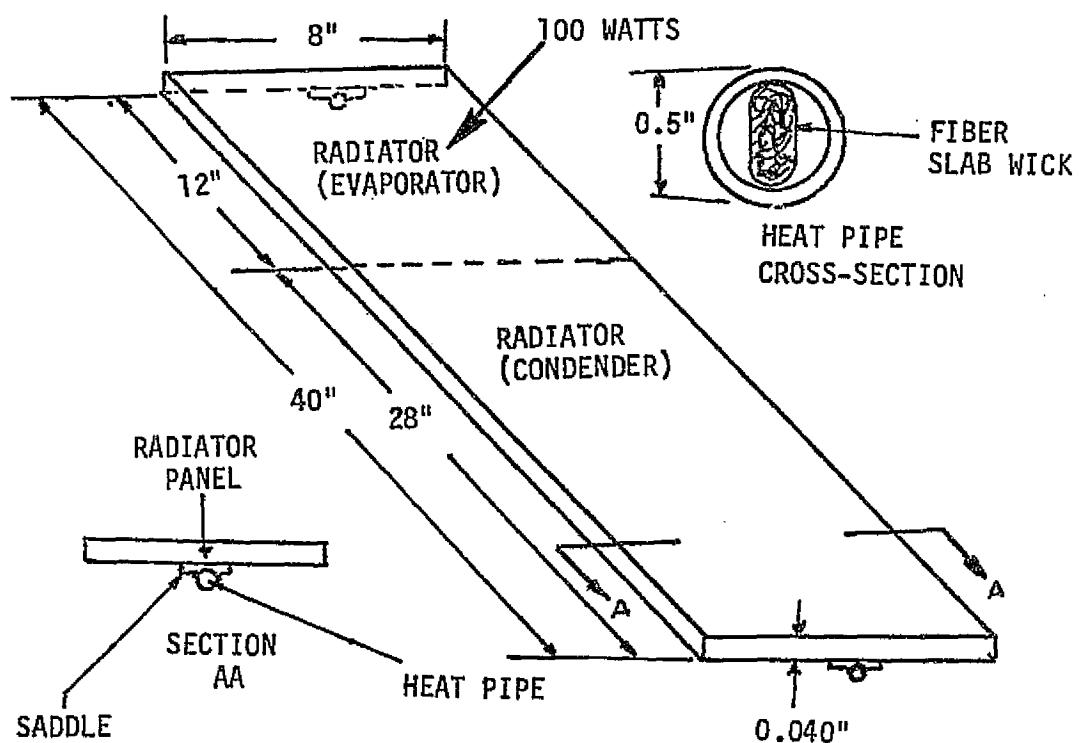
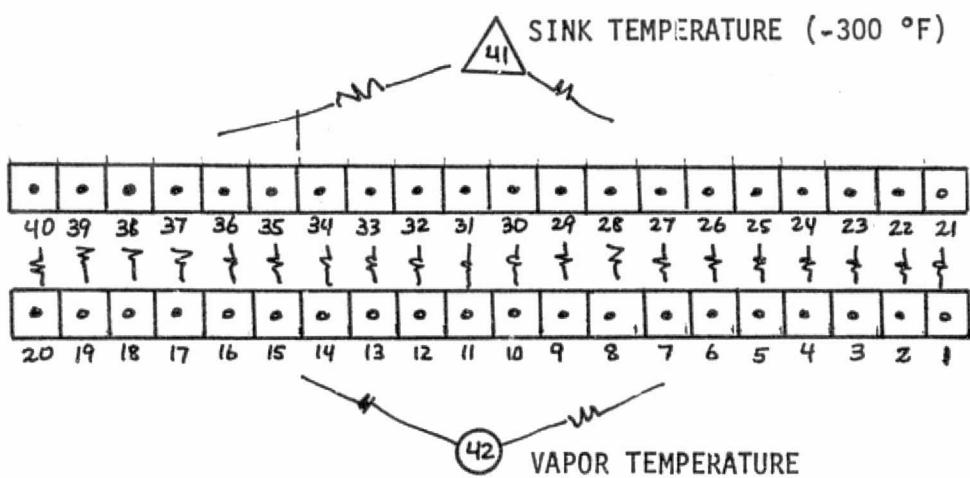


Figure 5-1. Simple Heat Pipe Model Geometry



1. $G_{i,j}$ $i = 1, 20$ $j = 20 + i$
2. $G_{i,j}$ $i = 1, 19$ $j = i + 1$
3. $G_{i,j}$ $i = 21, 39$ $j = i + 1$
4. Q_i $i = 35, 40$
5. $G_{i,j}$ $i = 21, 40$ $j = 41$
6. $G_{i,j}$ $i = 1, 20$ $j = 42$

Figure 5-2. Simple Heat Pipe Thermal Model

Steady state solutions to this model were obtained using SINDA in conjunction with subroutine VCHPZ. The subroutine, given the temperature distribution along the heat pipe and a gas inventory, calculates the location of the gas front, the wall-to-vapor conductances, and the vapor temperature which is treated as a boundary node.

5.1.1 Results

The vapor temperature (T_v), source temperature (T_s) and the length of the gas-blocked region (L_g) is shown in Table 5-1 for various gas inventories. For convenience, the gas inventories are also in units of (Lbf-ft/R) which is simply the number of moles (N) times the universal gas constant (R).

Table 5-1
SIMPLE HEAT PIPE MODEL: PERFORMANCE VS GAS
FOR 100 WATT LOAD

<u>N</u> <u>Lb-Mole</u>	<u>NR</u> <u>Lbf-Ft/R</u>	<u>T_v</u> <u>°F</u>	<u>T_s</u> <u>°F</u>	<u>L_g</u> <u>Inch</u>
0.	0.	70.06	75.70	0.00
6.5 E-7	0.001	70.26	75.90	2.06
6.5 E-6	0.010	75.22	80.74	7.30
3.2 E-5	0.050	97.00	101.00	13.94
4.8 E-5	0.075	108.03	111.80	16.87
6.5 E-5	0.100	119.29	123.90	18.00
8.0 E-5	0.125	126.80	130.10	19.90
9.7 E-5	0.150	133.70	138.00	21.60

The vapor temperature and source temperature are shown graphically as a function of gas (NR) in Figure 5-3. In view of the fact that the heat pipe in this thermal control model is meant to isothermalize the panel, it is revealing to refer to Figure 5-4 in order to appreciate how this function is diminished as non-condensable gas is generated inside the pipe. The most non-uniform temperature profiles are the result of gas inventories which are very unlikely to be attained in a carefully fabricated heat pipe. The performance for such large gas inventories are mainly of academic interest. However, they might be found useful in a reliability study in which a "worst" possible case, i.e. an anomalous heat pipe used in a spacecraft in a long interplanetary mission.

In order to evaluate the quality of the heat pipes of the test matrix of this program, let us calculate the time it takes for the source temperature of the model shown in Figure 5-1 to increase 5° F. Consider the worst heat pipe, SN 08, and the best one, SN 17, of the test matrix. The curves representing their temporal gas inventories, adjusting for the longer length of the heat pipe in the model, are for SN 08

$$N_{08} = 1.07 \times 10^{-6} + 3.15 \times 10^{-9} t$$

and for SN 17

$$N_{17} = 4.0 \times 10^{-8} + 2.73 \times 10^{-10} t$$

From Table 5-1, a 5°F increase in the source temperature is the result of a gas inventory of 6.5×10^{-6} lb. moles. The time to effect such a temperature increase is 5 years and 65 years respectively.

Assuming the acceptance criteria for a heat pipe to be integrated into the radiator panel so that after 5 years in operation the source temperature should not increase by more than 1.0°F, then a heat pipe of the quality corresponding to the chemically cleaned, refluxed with 10% water, would be acceptable. In fact, SN 17 or SN 18 after 5 years would have generated less than 6.5×10^{-7} lb-moles which, as shown in Table 5-1, results in an increase in source temperature

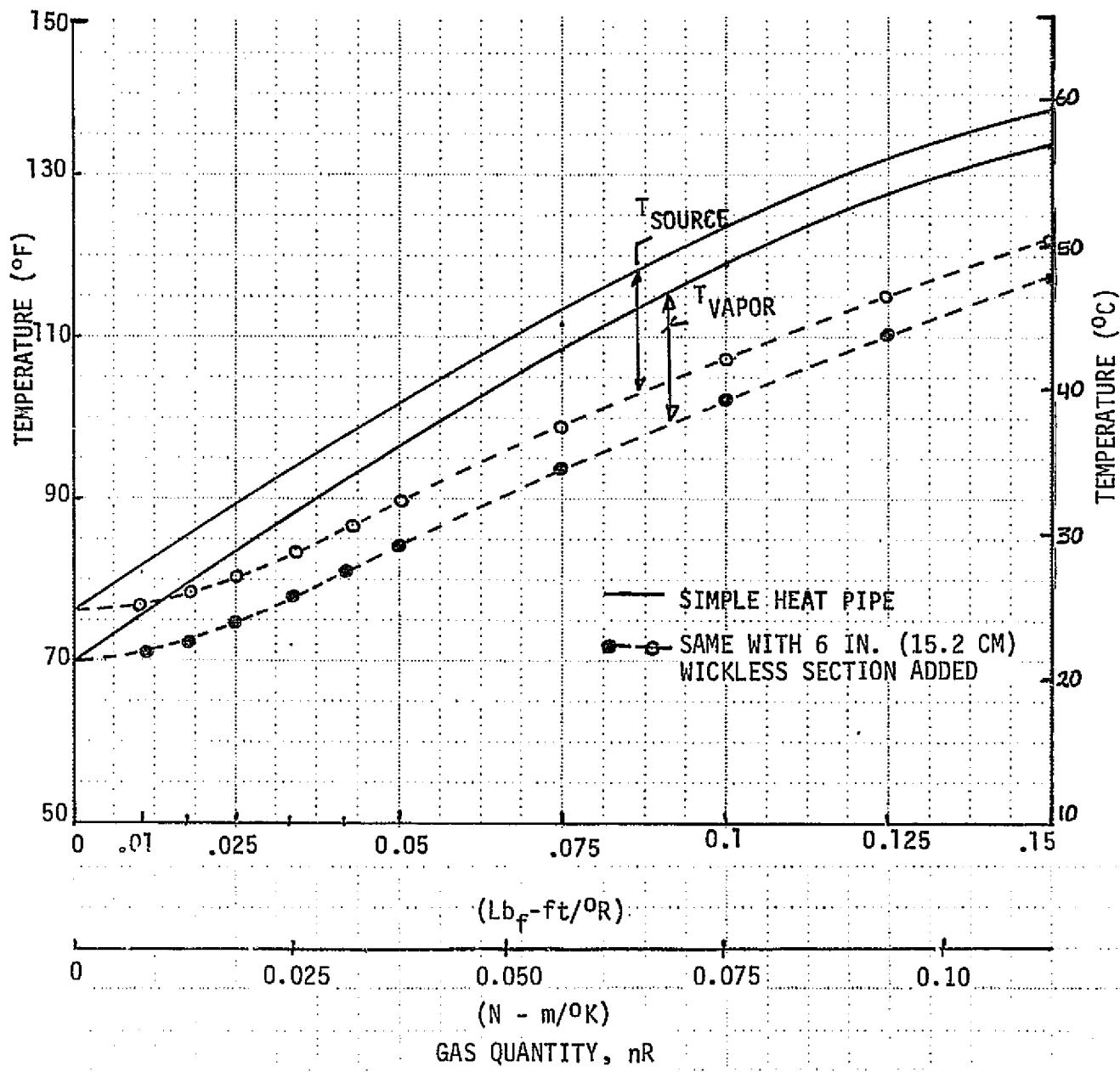


Figure 5-3. Simple Heat Pipe System Temperature As A Function Of Gas Content

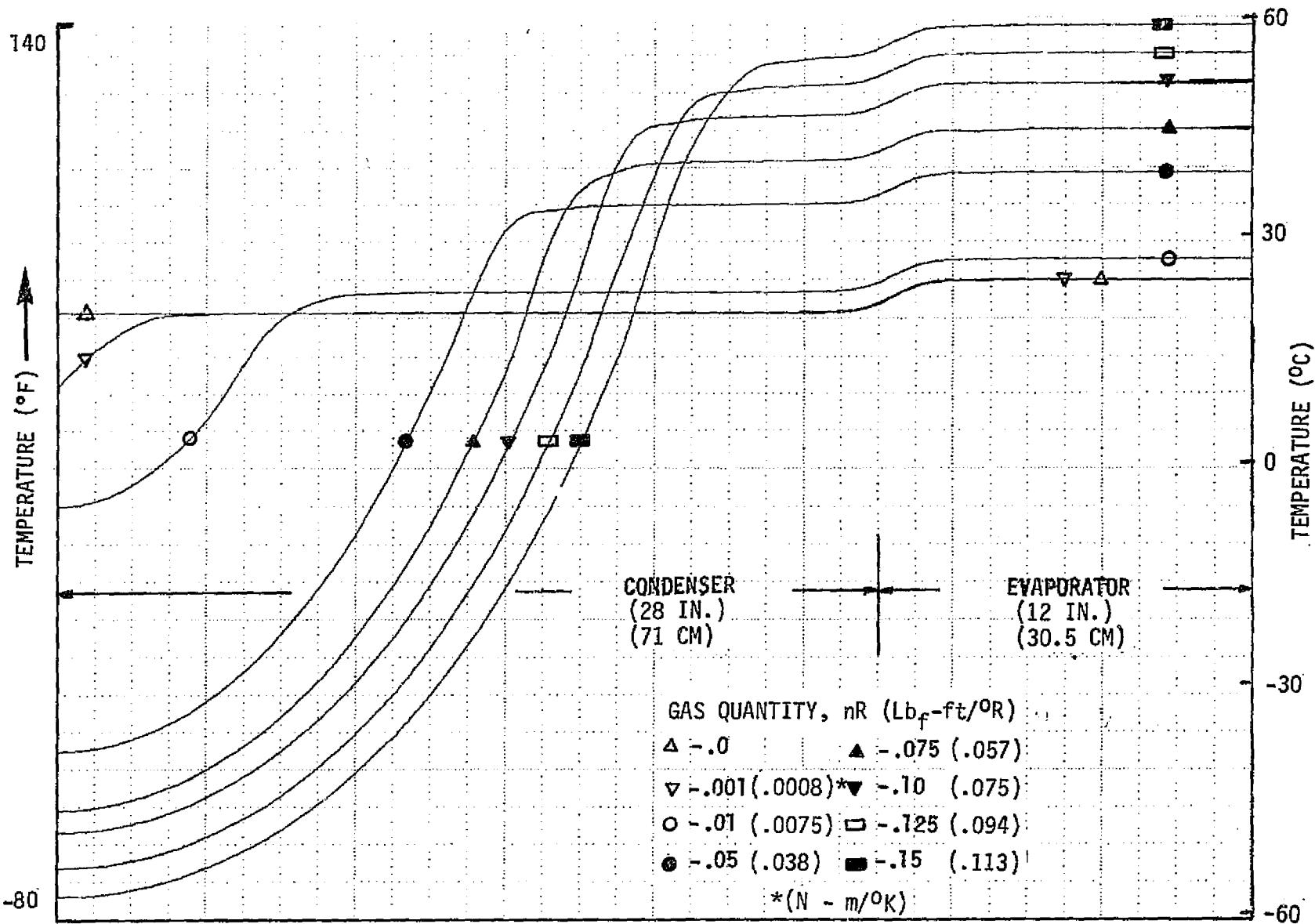


Figure 5-4. Temperature Profile Of Simple Heat Pipe Model

of less than 0.25°F.

Such an approach to meet a design criterion is undesirable since it does not provide a sufficient safety margin to allow departures from typical heat pipe performance as exemplified by anomalous heat pipes such as SN 16. An alternative approach is to modify the radiator model shown in Figure 5-1 by integrating a heat pipe with a short wickless section extending beyond the end of the condenser radiator panel as shown in Figure 5-5. This design change is a simple one provided the additional length of the assembly can be accommodated in the spacecraft particularly during launch.

The nodalization of the lump parameter model is shown in Figure 5-6. Steady state solutions, subject to the identical boundary and source conditions as in the previous model, were obtained with SINDA and subroutine VCHP2. The vapor temperature (T_v), source temperature (T_s), total gas length (L_g), and the radiator condenser section (\bar{L}_g) which is L_g minus the 6 inch long wickless pipe section, are tabulated for various gas inventories in Table 5-2. The plots of T_v and T_s are shown in Figure 5-3 where they can be compared to the results from the previous model.

To assess the effectiveness of this approach in diminishing the impact of gas generation on the performance of the assumed panel system, we revert to the temporal gas inventories of the worst and the best heat pipes of the test matrix, SN 08 and SN 17, respectively.

If the same acceptance criterion for a heat pipe is invoked, it can be seen from Table 5-2, that the worst heat pipe now becomes acceptable. Using the best heat pipe, it would take more than 65 years for it to generate sufficient gas to cause a 1°F increase in the source temperature.

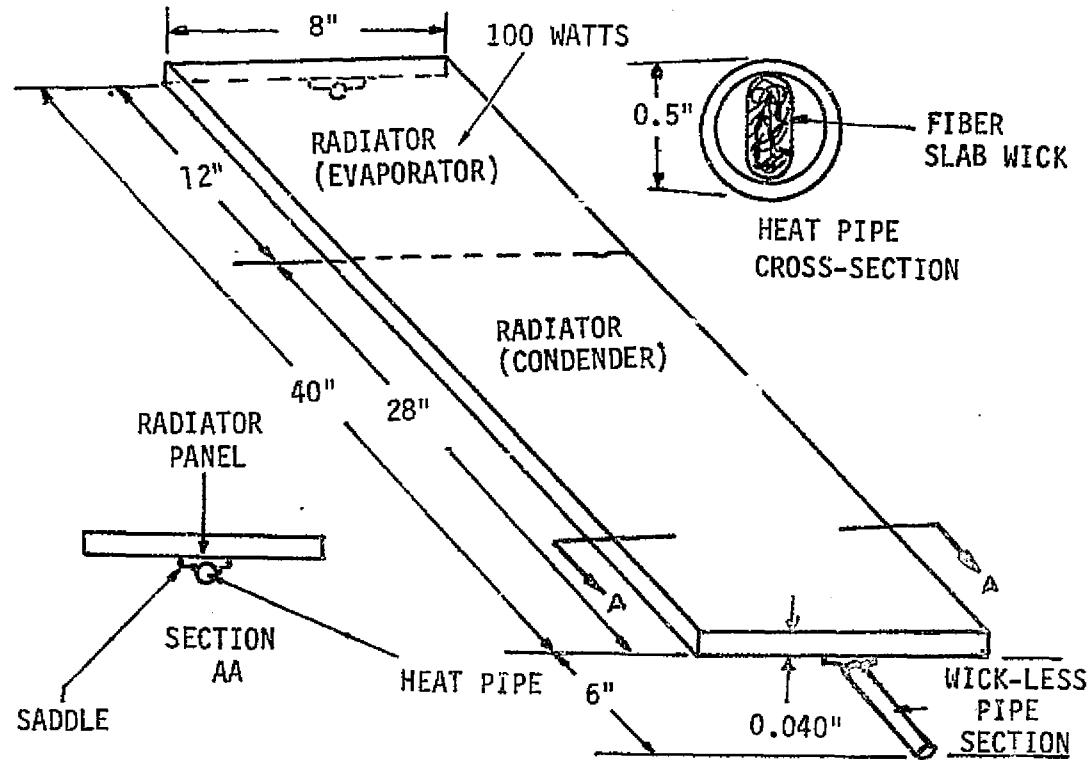
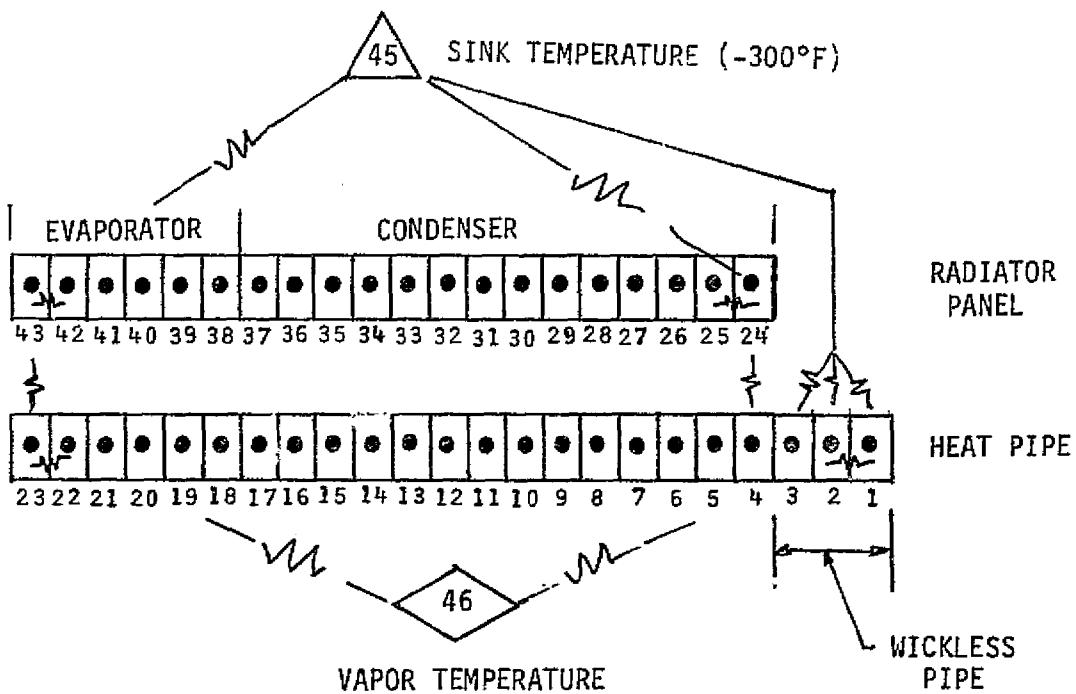


Figure 5-5. Simple Heat Pipe Model With 6" Wickless Pipe Addition



1. $G_{i,j}$ $i = 1, 23$ $j = 46$
2. $G_{i,j}$ $i = 1, 22$ $j = i + 1$
3. $G_{i,j}$ $i = 4, 23$ $j = 20 + i$
4. $G_{i,j}$ $i = 24, 42$ $j = i + j$
5. $G_{i,j}$ $i = 24, 43$ $j = 45$
6. $G_{i,j}$ $i = 1, 3$ $j = 45$

Figure 5-6. Simple Heat Mathematical Model

Table 5-2
 SIMPLE HEAT PIPE MODEL WITH WICKLESS PIPE SECTION
 PERFORMANCE VS GAS
 FOR 100 WATT LOAD

<u>n Lb Mole</u>	<u>Lbf-Ft/°R</u>	<u>T_v °F</u>	<u>T_s °F</u>	<u>L_g Inch</u>	<u>L_g Inch</u>
0.0	0.0000	70.04	75.70	0	- 6.00
6.5 E-7	0.0010	70.04	75.70	3.00	- 3.00
6.5 E-6	0.0100	70.98	76.60	9.83	3.83
1.2 E-5	0.0175	72.70	78.30	11.74	5.74
1.6 E-5	0.025	75.18	80.70	13.32	7.32
2.2 E-5	0.0333	78.24	83.70	13.97	7.97
2.7 E-5	0.0417	81.41	86.80	15.76	9.76
3.2 E-5	0.050	84.85	90.20	16.66	10.66
4.8 E-5	0.075	93.70	98.90	19.64	13.64
6.5 E-5	0.100	102.36	107.34	21.68	15.68
8.0 E-5	0.125	110.00	114.80	23.46	17.46
9.7 E-5	0.150	117.30	121.90	24.00	18.00

5.2 Variable Conductance Heat Pipe Model

A variable conductance heat pipe model also developed under TRW IRAD funds is shown schematically in Figure 5-7. The nodalization of the lumped parameter representation of the model is shown in the same figure.

A 0.5 inch OD, aluminum/slab wick/ammonia heat pipe over 40 inches long is connected to a 7.71 in^3 S.S. reservoir and mounted to a radiator condenser and an insulated heat source block by means of extruded saddles. Short stainless steel transition sections are located between condenser and reservoir, and condenser and evaporator. A heat flow rate of 100 watts is input uniformly in the evaporator block and is radiated at the condenser to a sink at -300°F . The nominal gas inventory is $0.200 \frac{\text{Lbf-ft}}{\text{in}^3}$ or 1.3×10^{-4} Lb-moles, which yields a temperature control band of 37.5°F from turn-on at 36.5°F to full-on at 74°F . This variable conductance heat pipe thermal control model was also solved using SINDA and the subroutine VCHP2.

5.2.1 Results

Steady state solutions were obtained for various increments of gas inventory to assess the changes in the control characteristics of the heat pipe as the result of internal gas generation.

The turn-on temperature ($T_v, \text{ On}$), full-on temperature (T_v, F) and the source temperature (T_s) at full-on conditions are tabulated in Table 5-3 and shown graphically in Figure 5-8 as functions of gas increments, $\text{NR}(t) - \text{NR}(0)$. It can be seen in the figure that the full-on temperature, and consequently the source temperature, increase linearly with increasing gas increment.

On the other hand, the turn-on temperature increases non-linearly with gas approaching the full-on temperature in an asymptotic fashion. Thus, an increase in the gas inventory improves the control temperature characteristic of the VCHP system although

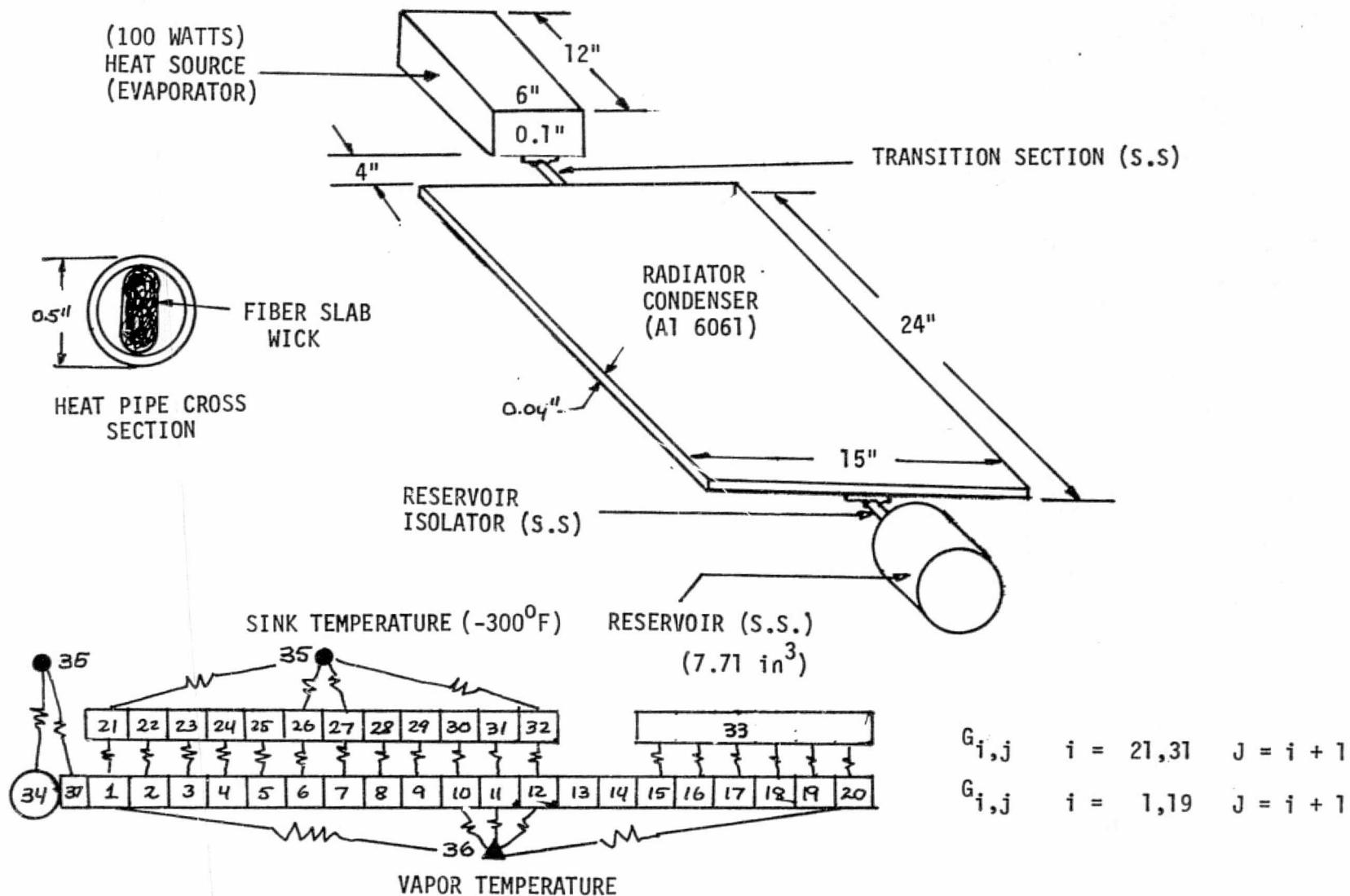


Figure 5-7. Variable Conductance Heat Pipe Geometry And Math Model

Table 5-3
 VCHP MODEL
 TEMPERATURE VS GAS INCREMENT
 FOR 100 WATT LOAD

NR (+) -NR (0)

<u>$Lb_f \sim Ft/^\circ R$</u>	<u>T_v, On</u> <u>$^\circ F$</u>	<u>T_v, F</u> <u>$^\circ F$</u>	<u>T_s</u> <u>$^\circ F$</u>
0.00	36.55	74.11	83.40
0.001	36.81	74.19	83.48
0.010	39.15	74.98	84.26
0.050	47.95	81.02	90.31
0.075	53.05	84.36	93.63
0.100	58.22	87.74	97.02
0.125	62.66	91.22	100.50
0.150	66.89	94.54	103.82

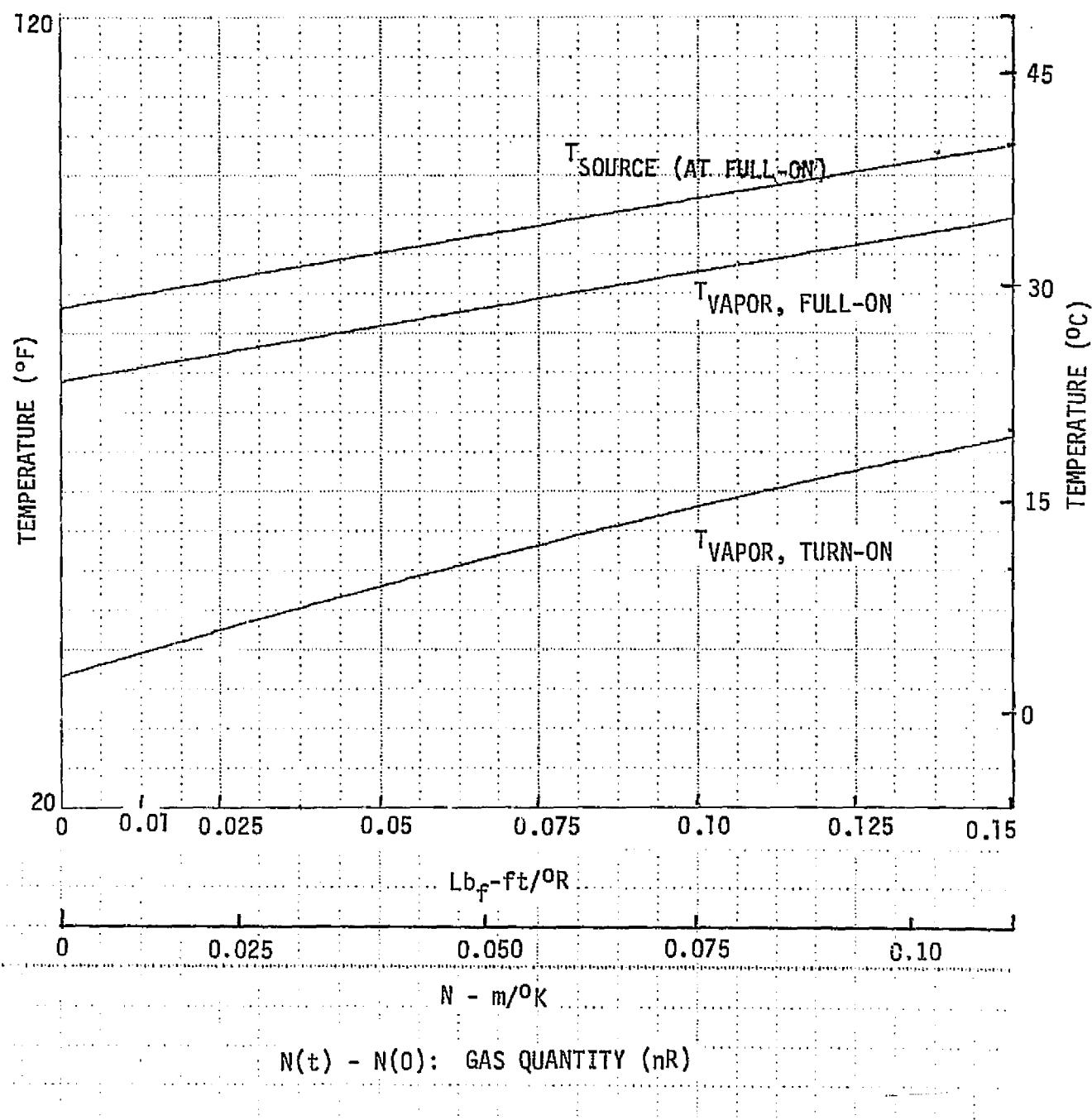


Figure 5-8. Variable Conductance Heat Pipe Performance Characteristics As A Function Of Incremental Gas Load.

at the expense of an elevation of the overall temperature level.

To illustrate a change in the performance of the VCHP system resulting from gas generation, let us again consider gas data corresponding to that of heat pipes SN 08 and SN 17. Assuming it is desired to calculate the time required to cause an increase of 5°F in the full-on temperature. From Figure 5-8, such an increase in temperature corresponds to a gas inventory increment of $NR(t) - NR(0) = 0.0375 \text{ Lb}_f\text{-Ft}/^{\circ}\text{R}$ or $N(t) - N(0) = 2.43 \times 10^{-5} \text{ Lb}$ moles. It is calculated that for a heat pipe with similar gas performance as SN 08 or SN 17, it would take from 20 to 243 years, respectively, to effect an increase in the original gas inventory resulting in a 5°F elevation of the turn-on temperature.

6.0 SUMMARY AND CONCLUSION

The materials compatibility test program conducted under Contract NAS3-21200 has examined the effect of adding water to ammonia used to reflux aluminum/ammonia heat pipes. Phase 1 tests were directed at analysis of coupon sized samples to provide a basis for selecting processing variables for Phase 2. Optical measurements of the coupons were used in an attempt to quantify the effect of water addition during reflux tests. The results from Phase 1 provided evidence that the concept of water passivation was sound, although the evidence was qualitative and not quantitative.

Phase 2 of the program consisted of the fabrication of an 18 heat-pipe-matrix. Half of the pipes were chemically cleaned and half were solvent cleaned. Each group of heat pipes was further divided into sub-groups of three heat pipes which were refluxed with ammonia which had either 0, 3 or 10% water added. The long term gas generation of these heat pipes was measured over a 283 day test period. Extensive data analysis was used to evaluate the effectiveness of the processing variables.

The conclusions of the heat pipe tests show that the passivation effect of water added during the reflux of chemically cleaned heat pipes is beneficial for aluminum/ammonia heat pipes, and is not advantageous (possibly even disadvantageous) when used with solvent cleaned aluminum/ammonia heat pipes.

Calculations were performed to quantitatively assess the effect of gas on simple (isothermalizer) and variable conductance heat pipes (VCHP's). The data reported, although taken at an accelerated temperature of 80°C, had no significant impact on the performance of VCHP's, even for as long as 20 years of operation. It was shown that simple isothermalizing heat pipes were more sensitive to non-condensable gas generation. The accelerated life test data indicate a possible significant impact of non-condensable gas on simple heat pipes. It is shown, however, that a small "reservoir"

included in the heat pipe design can reduce potential impact significantly.